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THE INSTITUTION OF PETROLEUM TECHNOLOGISTS.

THE ONE HUNDRED AND FIFTY-THIRD GENERAL MEETING of the Institution of Petroleum Technologists was held at the Royal Society of Arts, John Street, Adelphi, W.C. 2, on Tuesday, December 12th, 1933, Mr. T. DEWHURST, President, in the Chair.

The Secretary read the names of candidates nominated for election and the following list of members elected :—

As Members.—Alfred Bentz, Nelson Betancourt, Harold Nevison Cattle, John Victor Delves, John Leslie Gregory, Stanley John Ireland, Emeric Kroch, Gordon McIntyre, Masakichi Mizuta, Herbert Hutcheson Moor, Reginald Killmaster Stratford.

As Transfer to Members.—Percy Robert Clark, Stanley R. Wilson.

As Associate Members.—Sydney Rushton Backhouse, Edward Locker Delmar-Morgan, William Webster Downs, John Moir, Roy Taylor Pearson, John Scott Preston.

As Transfer to Associate Members.—Tewdwr Griffith Bowen Davies, Herbert Harland, Giles Philip Eliot Howard, Maurice Kamen Kaye, Otto Leslie Shaw.

As Students.—William Reid Boyd, John Leslie Childs, Alfred John Haworth, Richard Etienne de Mestre, Nadim Pachachi.

The President announced that the Council had decided that on the last Friday in June, 1934, an Overseas Meeting would be held at which Reports on the Progress of Naphthology would be discussed at morning and afternoon sessions, followed by the Annual Dinner in the evening. It was hoped that this would lead to a considerable attendance of Overseas members who would be on leave in this country at that time. Further particulars would be announced in due course.

He desired also to draw the attention of members to the very interesting programme which the Committee of the Students' Section (London Branch) had arranged for the Session, and which should attract students from university colleges and technical schools, and the junior members of the staffs of oil companies, and thus aid in the recruitment of Student Members of the Institution.

The Secretary had been empowered to write to the Secretaries of Oil Companies and other prospective employers, drawing their attention to the Appointments Register of the Institution.

The main business of the present meeting was the presentation of a paper by Lieut. J. S. A. Salt on "Air Survey." Lieut. Salt had read an important paper before the World Petroleum Congress on "Some Fundamental Aspects of Air Survey," but there had not been time to show a large number of lantern slides in illustration of the paper, and discussion had also been restricted.

Members would be glad that Lieut. Salt had summarised his Congress paper, and that they were to see the slides and to have a full discussion of the paper that evening.

Air Survey.

By Lieut. J. S. A. Salt, R.E.

The technical aspects of Air Survey have been dealt with in a paper read before the World Petroleum Congress in July, 1933. ("Some Fundamental Aspects of Air Survey.") The treatment there, though elementary, was fairly complete, and reference should be made to it if a concise framework of the technique is required. It will be convenient here to summarise the argument, and emphasise those aspects which need to be particularly stressed at the present time.

Map making is a vital social function. Without a complete series of accurate maps, no organised administration of a country can be successfully carried out. They are used for a large variety of purposes, and it is impossible to predict all the circumstances in which they will be needed. The discovery of mineral deposits, for instance, may require the immediate use of large scale maps for geological prospecting, road and railway communications, and general engineering, and this is most likely to happen in an area previously almost uninhabited. Maps must therefore be made in advance according to an enlightened long-term policy. More than a century ago, the broad foundations for the mapping of England were made, and from that original foresight we are benefiting to-day. There is little evidence, however, that we intend to honour this heritage and observe the same principles ourselves.

Survey may be divided roughly into three stages :—

(1) Geodetic Survey—the broad framework.

(2) Topographic Survey—the depicting of physical features.

(3) Drawing and Reproduction—publication in useful form.

Geodetic survey is analogous to the steel framework of a modern building : it is the backbone on which everything else depends, though it does its work away from the public view. All topographic survey should rest on a geodetic framework. This is the stage which supplies the "copy" for the subsequent publication, but though the demand for the finished product increases every day, the amount of "copy" collected is, in the name of economy, steadily decreased. A map when produced is only beginning its life : it must evolve with the community and record its progress. At the present moment, we have not only practically ceased producing new maps in the British Empire, but we are not even

keeping up to date those that exist. There is an increasing need, therefore, for a method of survey which is both cheap and speedy, and it is this function that Air Survey is admirably suited to fulfil.

The problems of Air Survey have been exhaustively studied, and there is now a sufficient variety of high-class equipment and of experience all over the World to decide immediately on the most efficient method of tackling any particular job. The use of air photographs, moreover, emphasises very strongly the advantages to be gained by treating the problem on a broad basis and co-ordinating the various interests at the start. By so doing, a plan may be evolved which fulfils various needs at the same time and supplies a solution to each at a fraction of the cost that would have been incurred by any one interest functioning singly. To bring about such co-operation, however, requires an organisation which, by the extent of the problems involved, can hardly be based on less than imperial lines. It is to be hoped that some such organisation may, in the near future, be evolved.

It might be expected that there would be more to say about the application of Air Survey to the special needs of petroleum technologists. Study of the subject, however, can only engender the conviction that a sectarian presentation would actually be prejudicial to its own interests. Before the foundation of the means of carrying out a plan can be securely laid, technical details are of purely academic interest. The necessity at the moment is to initiate action. " Waiting till prosperity returns " is not enough : prosperity follows activity rather than precedes it. The best interests of petroleum technologists will therefore be served if they satisfy themselves of the application of Air Survey to their problems, relate this application to the broad framework of Survey as a whole, and then press for a solution on this broader basis. An imperial point of view is not only in the best interests of Survey as a whole, *i.e.*, recognising its social consequences in many generations of men, but from the purely technical point of view, Air Survey cannot hope for the best, and cheapest, results unless the organisation carrying it out is assured of continuity. Where a high standard of skill is involved, a long period of study and practical experience is necessary for the highest efficiency, and the intermittence of demand suffered by companies operating under private contract militates against this condition. Moreover, a feature of efficient production is the harmonising of the various stages so as to avoid a " bottle-neck." In Air Survey, the photographic crew, given favourable weather conditions, can carry out enough photography in a few days to keep a ground party occupied for several months. A specialised flight of aircraft could, therefore, carry out most of the necessary photography by flying round from place to place according to the

weather conditions, thus being continuously occupied. The ground parties would have a more local flavour. Plotting should be carried out at a few centralised drawing and reproduction offices where the latest and most efficient equipment would be permanently in use. The three separate functions would be harmonised with a view to continuous production, and an Imperial Survey Organisation is admirably suited to achieve this.

Progress in this direction can be made if those intending to place contracts for Air Survey realise that by co-ordinating their interests with those of others, and by demanding a solution on a broader basis, they themselves will be the ultimate gainers.

During the reading of the paper a number of pictures were shown on the screen, illustrating the types of photographs produced, and the apparatus for examining them and for transferring the information to maps.

DISCUSSION.

The President was sure the members would agree that the printed paper gave but little indication of the scope and fascination of Lieut. Salt's demonstration. Personally he had received the impression that he had been listening to a master of his subject, but he hoped that the paper and the demonstration had not been so complete and flawless as to preclude criticism and amplification.

Mr. H. Hemming remarked that Lieut. Salt had dealt very thoroughly with the application of air photography to surveying and, if he might be permitted to do so, he himself would like to make a few remarks about its actual use in connection with economic development, particularly in regard to mineral prospecting. Lieut. Salt had referred to the necessity of co-ordinating interests for the carrying out of air surveys. In that connection he would like to tell the members of the operations which were now being carried out in Western Australia by the Western Mining Corporation, who are looking for gold there. The Corporation was representative of a number of interests who had got together in order to have air photography carried out over some 88,000 square miles of mineral-bearing country. Being of the opinion that much useful data would result from the air photography in addition to that which they required for their own purposes they proposed to invite the Australian Government to make full use of the air survey organisation and have access to the experience and data gained from the operations. It might interest the members to know that the Western Mining Corporation had decided to have the air survey carried out as a result of the very successful work

which had been done on the Rand in South Africa. He desired to show one or two photographs from which it would be seen how the work would be carried out.

The first slide was a photograph of the Wanderer Mine in South Africa and it depicted quite a lot of geological features, a particularly striking feature being the contact between two forms of geology, which showed up very distinctly. The next picture would give the members an interpretation of the photograph. This photograph had been taken at about 10,000 ft. by the Aircraft Operating Co., Ltd., and he had to thank the Wanderer Consolidated Gold Fields for allowing it to be shown.

The next slide showed rather an interesting comparison of two separate and independent interpretations. The Mining Engineer of the Company in London had had sent to him a stereoscopic pair of these air photographs, and, without actually knowing the geology of the mine, he had drawn in what appeared to him to be features of interest for the geologist on the prospect to look at. While he had been doing that in London, the geologist out in Africa had taken another pair of stereoscopic photographs, printed from the same negatives, to the prospect, interpreted them and drawn in the actual features as shown on the photographs. This slide showed the interesting comparison which the two interpretations made. In both cases the main features were almost identical. Actually the Wanderer Mine had been highly geologised on the ground, and yet the air photographs had yielded a great deal of valuable information which had not been known before they had been taken.

The next slide showed another photograph in the Wanderer area. It clearly depicted a fault disclosed through the bend in the ridge seen running across the upper part of the photograph. It was interesting to notice how, even in certain heavily wooded areas, faulting showed up, although normally it would not be noticeable to the prospector on the ground.

The next slide was a photograph which had been lent to him by New Consolidated Gold Fields, and it showed a sink-hole on the extension of the Witwatersrand Reef. This sink-hole was associated with the faulting system, and at that particular point he understood that the Reef had dipped about 2000 ft. under the dolomite. The photograph had been taken at about 10,000 ft.

The next slide he showed, because it was a test photograph which had been taken with an Eagle IV. camera made by the Williamson Manufacturing Co., which was now being used for the air survey in Western Australia. It showed how the lenses and cameras were improving, and how as the result sharp detail right up to the edges of the picture was secured.

Before concluding he wished to add a few words about the Western Australian operations, as he thought that they might interest members. There the area to be examined covered about 88,000 square miles of country. The company responsible for the survey had wished to know which areas they were to take up and prospect. Therefore an expedition consisting of two D.H. Dragon aeroplanes, a complete set of directional wireless, and a fleet of six motor vehicles had been sent out with all the latest survey and photographic equipment. The preliminary test flights had been carried out satisfactorily. In the little-known areas the 'planes were going to fly grid lines at regular intervals across, taking vertical overlapping photographs, thus securing photographic samples of the areas, the photographs then being studied under the stereoscope. During the whole time that the survey was in progress the operations would actually be controlled from the Manager's office. The Manager would have alongside of him a wireless operator who would be in touch with the motor lorries in the field, stationed in positions which would enable bearings to be taken on the aeroplane, so that the whole time the machine was flying its position could be plotted. Should the geologist in the aeroplane wish to communicate anything he could do so, as the operator would be in direct touch with the machine. In that way it was hoped very quickly to obtain some general idea of the geology of the country, and then if anything of interest was seen it would be photographed vertically and examined in the stereoscope, and those photographs would be used to enable the prospector to find his way to the location and in its detailed examination.

He said that there was abundant proof available as to the value of air photography for geological prospecting and mapping, but it was important that the photographs should be interpreted and used by qualified experts. Much harm had been done in the past through unqualified enthusiasts seeing more in the photographs than was actually there.

It was not claimed that air photographs did away with the field work. What they did was to provide the geologist with clues and a means of finding his way to them. The final prospecting had to be carried out on the ground by the normal methods followed hitherto.

Finally Mr. Hemming said that he wished to add his appreciation of Lieut. Salt's interesting paper. In his important position of Research Officer to the Air Survey Committee at the War Office Lieut. Salt was doing very valuable work, and had shown that he was all out to help all those who, like himself, were endeavouring to establish air surveying as a permanent and readily available service in the Empire.

Mr. L. Owen said that he thought he could speak for most of the members of the Institution when he said that it was an absolute "eye-opener" to realise how the matter of contouring had improved within a recent period. In the past one had always been very suspicious about aircraft contouring, but the diagrams which Lieut. Salt had shown, and the apparatus he had described, opened up an enormous vista to the ground geologist and removed most of the objections which he had had to taking contour maps constructed from air photographs too seriously.

There was one small point on which he would like to caution Lieut. Salt, if he might presume so to do, and that was with regard to infra red. Infra red photographs, when they had been speeded up and technique had been somewhat improved, were going to be one of the most powerful weapons in finding out things that neither the man on the ground with his ordinary human eye nor the observer in the air also with his ordinary human eye could see. Such photographs, he was certain, would be the means of discovering lots of facts which had been passed over quite blindly in the past.

Mr. T. R. H. Garrett stated he could not add very much to the discussion as all these wonderful photographic inventions had taken place since his time. He did not, however, agree that the paper was entirely uncontroversial. He thought the first slide, which showed the state of mapping in the world, raised a very controversial point. On it, Great Britain was coloured black, indicating that the mapping in the case of Great Britain was "good." He had just been working in Wales with the 6 in. and 1 to 2500 scale maps, and as a result of his experience he would say that the mapping of part of this country was extremely bad. He was certain that even the old air photographs which were taken during the war would have made very much better maps.

Mr. A. Beeby Thompson said he felt sure that all the members were very grateful to Lieut. Salt for his instructive paper, but personally he envisioned many difficulties in regard to the general use of air photography. For instance, in a number of countries which were being prospected for oil difficult climatic conditions, such as sand storms, fogs and "sand devils," must necessarily cause a great deal of time to be wasted when there were several aeroplanes in an expedition on the ground.

He would like to know the time of day at which the photographs shown by Lieut. Salt on the screen had been taken. He had done a little flying himself over structures, and it seemed to him that the time of day observations were made and the intensity of light made a very great difference, particularly in regard to shadow effects which brought topographical features into prominence.

Lieut. J. S. A. Salt, in reply, said he was grateful to Mr. Owen for reminding him of the value of infra red photography for the purpose of identifying normally invisible forms. The point that he had stressed was rather that from the point of view of *topographical* mapping, the results are not likely to be of great practical importance. What one had hoped for from infra red photography was the ability to photograph on dull foggy days, if necessary, and for that purpose the outlook was not too bright, but for identifying different kinds of soils and vegetation, the use of stained emulsions and colour filters, of which infra red photography is merely one example, is only in its infancy. The same method might even extend to underground features.

With regard to the Ordnance Survey maps, he wished that the Director General of the Ordnance Survey had been present to answer Mr. Garrett's remarks. He knew the reply which the Director General would give, namely, that it was a question of cost.

The present position of Ordnance Survey Maps was as follows. Successive reductions in funds and staff led some time ago to the impossibility of keeping the 1/2500 maps up to date. Revision was then planned on the basis of the 6 in. to the mile maps (1/10,560), with a cycle of about 20 years. But recent further economies had forced the abandonment of all revision of rural areas, and even in urban areas only those exhibiting the greatest development could be undertaken.

Mr. Garrett said the map he had mentioned must have been done at about B.C. 45.

Lieut. Salt said in that case it certainly was not the fault of the Ordnance Survey. Anyway, any defects in the existing maps of England arose from lack of funds. The maps were unavoidably getting rapidly out of date, and if Mr. Garrett found that in his practice they were so bad, the only remedy was to do what he could to urge the allotment of sufficient funds to the Ordnance Survey to enable them to carry out their vital national task.

With regard to the problem of blowing sand, and the difficulty of taking photographs in adverse weather conditions, Mr. Beeby Thompson had mentioned the need for keeping " several " aircraft on the spot waiting for a suitable day. That was not normally the case. A single aircraft, when once started, could photograph at a rate of about 200 square miles an hour, and could produce in a few days enough to keep the ground party, or several ground parties, busy for several months. There, again, the question of co-ordination of interests arose. If several different surveys could be organised at the same time, one aircraft might suffice for the lot. It could fly about from place to place according to the weather reports obtained

by wireless. Any independent and isolated solution was bound to be uneconomical.

It was difficult to lay down a definite rule as to the time of day when photography should be carried out. In desert country it was normally best to photograph in the early morning, because by mid-day the wind had started to blow sand about a few feet from the ground. This obscured the detail, and gave the appearance of a fogged plate. In most other countries the principal factor was cloud, and one had to photograph when one could. Freedom from this restriction was improving. In Canada, for instance, they now found that they could take very good photographs underneath a cloud bank, whereas a few years ago the technique still suffered from the bad light conditions.

A hearty vote of thanks to Lieut. Salt for his paper and demonstration concluded the meeting.

INSTITUTION OF PETROLEUM TECHNOLOGISTS.
TRINIDAD BRANCH.

THE THIRTY-THIRD GENERAL MEETING of the Trinidad Branch of the Institution of Petroleum Technologists was held at the Apex Club, Fyzabad, on Wednesday, March 1st, 1933, Mr. G. Hugh Scott, B.Sc., Branch Chairman, in the chair.

The following paper was read :—

Some Notes on Drilling Muds.

By PERCY MEYER, B.Sc., F.I.C. (Associate Member).

With deeper producing horizons and higher reservoir pressures the subject of drilling muds is becoming increasingly important. In the last year or so an additional factor in Trinidad has been the Schlumberger electrical coring apparatus ; which, in the case of deep tests, requires high density mud sufficiently thin to enable the plummet to sink to the bottom of the hole.

Duckham [1] enumerated some fourteen functions which should be fulfilled by a drilling mud. A full knowledge of the subject is attainable only by extensive research.

It is proposed in this paper to review broadly our present knowledge of muds, having regard to local conditions, with a view to securing cheap and efficient field operations.

PHYSICAL CHARACTERISTICS.

It is well known that many colloidal suspensions do not behave as liquids, but are better described as semi-solids. Such substances may be regarded as possessing both yield point and viscosity characteristics ; while a true liquid possesses no yield point. Results with a Stormer, Redwood or other simple viscometer are therefore not very informative, since the result is a compromise between two unknown factors.

Herrick [2] appears to have been the first to regard the flow conditions of drilling mud as dependent on the shear force or yield point of the mud, as well as upon viscosity.

Both factors may be measured simultaneously by determining the rate of flow through a capillary at various heads. A simple apparatus is shown in Fig. 1. The results when plotted graphically give a straight line relationship, as shown in Fig. 2, from which both the viscosity and shear force may be calculated when the dimensions of the capillary are known.

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[1] Duckham, " The Chemical Aspects of Drilling Muds," *J. Inst. Petr. Techn.*, 1931, **17**, 153–182.

[2] Herrick, " Data on Flow of Rotary Drilling Muds," *Oil & Gas J.*, Feb. 28th, 1932, p. 16.

Herrick was concerned mainly in calculating pressure data in regard to circulating mud in the well. Once the shear force* is overcome, the mud behaves as a liquid. The shear force is, however, important in other connections, as will be shown later.

Data for Barytes—Clay Mixtures.

Different clays vary considerably in colloidal properties. Farnham [3] gives curves for various muds showing wide divergencies. The local Cyclammina clay is not absolutely homogeneous, but muds prepared from it are generally comparable in properties.

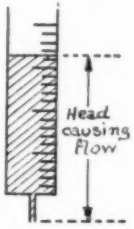

FIG. 1.

FIG. 2.

Shear force and viscosity curves for Cyclammina clay muds of various densities, are given in Fig. 3, together with curves for barytes-clay mixtures. The determinations were made at room temperatures (80° F.–90° F.).

* The term "shear force" is here used as synonymous with "yield point." It represents force per unit area, being of dimensions $\frac{M}{LT^2}$; while viscosity is of dimensions $\frac{M}{LT}$.

[3] Farnham, "Analytical Considerations of Drilling Muds," *Petr. Eng.*, February, 1931.

With clay alone, the shear force rises slowly with increasing density. Herrick found for Californian mud F=0·02 (D–65), while the Fig. 3 results are expressed by F=0·018 (D–64) (where F=shear force, lb. per sq. ft. and D=mud density, lb. per cu. ft.).

The viscosity rises steeply at densities above 75 lb. per cubic foot; this steep increase indicating the colloidal nature of the clay.

Fig. 3 shows curves for clay suspensions weighted to 100 lb. and 130 lb. with various samples of barytes. The effect of barytes is more apparent in the 130 lb. muds than in the 100 lb. muds. It will be seen that the quality of barytes has an appreciable effect on the mud produced. No simple correlation between viscosity and shear force is apparent; for instance, 130 lb. mud prepared from sample 3 barytes showed highest viscosity and lowest shear force.

Quality of Barytes.

The barytes samples all had a sp. gr. between 4·2 and 4·4; and were, as far as is known, of comparable fineness. The No. 4 sample showed, however, a very poor wettability by water or clay suspension. When dropped into water and stirred, it formed clots which were air-bound. The 100-lb. and 130-lb. muds, prepared with clay suspension by means of a pestle and mortar, contained an appreciable amount of entrained air; and were thicker than the other corresponding mixtures. Reference to Fig. 4 shows that this was due to a much higher shear force, the viscosity being comparable with that of other muds.

Travis[4] writes as follows in this connection :—

"Some substances are easily wetted while others are resistant to wetting and, in a great number of instances due to the affinity they have for absorbing air on the surface of the particles, the particles do not come in contact after the powder is agitated in the presence of such liquid. An excellent example of this is in the case of very finely divided calcium carbonate. If this is added to water and agitated, one may obtain a thick paste after the addition of about 25 per cent. of carbonate. If this material is then passed through a so-called colloid mill, it is possible to shear off the air cushions and get a proper contact angle of the water with the powder. This dispersion upon discharge from the colloid mill, will be found to be very fluid again, due entirely to the elimination of the air cushions. An additional 25 per cent. of carbonate can then be added to the dispersion and the operation repeated. A material will be obtained which is at least 50 per cent. calcium carbonate and yet very fluid. This demonstrates that the original pasty condition was caused by the adsorption of air on the fine particles."

[4] Travis, "Mechanochemistry and the Colloid Mill," Chemical Catalog. Co., New York, 1928.

The use of a colloid mill would possibly produce the thinnest barytes-clay mixtures obtainable. As shown later, however, heavy muds of sufficiently thin consistency may be prepared without its use, provided the clay concentration is kept sufficiently low.

It is evident, however, that the wettability of the barytes is a matter of importance. The factor involved is the surface tension between liquid and solid phases. Methods for evaluating this experimentally have been developed.[5]

Barytes of the poor wettability referred to above is not commonly encountered. The simple test of stirring into water and observing any clotting tendency, affords a useful indication of the suitability of the barytes for drilling muds.

Regarding field use, barytes of poor wettability leads to the formation of viscous mud which is to some extent gas-cut when prepared, due to entrained air. It is probable also that the mud will the more easily become gas-cut in use.

It may be noted in passing that the results in Fig. 3 were obtained by means of a capillary viscometer in which very thick muds could not be handled. Thick muds in use on the field may have a shear force of 1 lb. per sq. ft. or more.

Stability.

The muds should neither settle out on standing with a dense lower portion and a light upper portion ; nor (except when required for special reasons) should the mud gel on standing. Some results shown below were obtained in the following way : a 100-ml. cylinder filled with mud was allowed to stand 24 hrs. undisturbed. The top 50 ml. was decanted and the average density of the top and bottom 50 ml. portions was determined. The mixtures were all originally of about 100 lb. per cu. ft. density, the only variable being the amount of Cyclammina clay present.

Densities in Lb. per Cu. Ft.

Clay Suspension	Original Barytes-Clay Mud.	After 24 hours. Top.	After 24 hours. Bottom.
62·3 (water only)	105·0	62·3	147·7
63·5	98·0	62·5	133·5
66·3	103·0	88·5	117·5
70·2	105·5	105·	106·0

It is evident that a certain minimum clay concentration, of about 68–70 lb. per cu. ft. is necessary to ensure stability in regard to settling. Further similar experiments showed that thin stable 130-lb. muds could readily be prepared with simple clay-barytes mixtures.

Regarding gelling, with clay concentrations between 68–70 lb. per cu. ft., the lower portion after standing was sufficiently

[5] Davis and Curtis, *Ind. Eng. Chem.*, 1932, **24**, 1137 (with bibliography).

thin to flow reasonably freely from the cylinder. With higher or lower clay concentrations, also with barytes of poor wettability, the lower half was gelled.

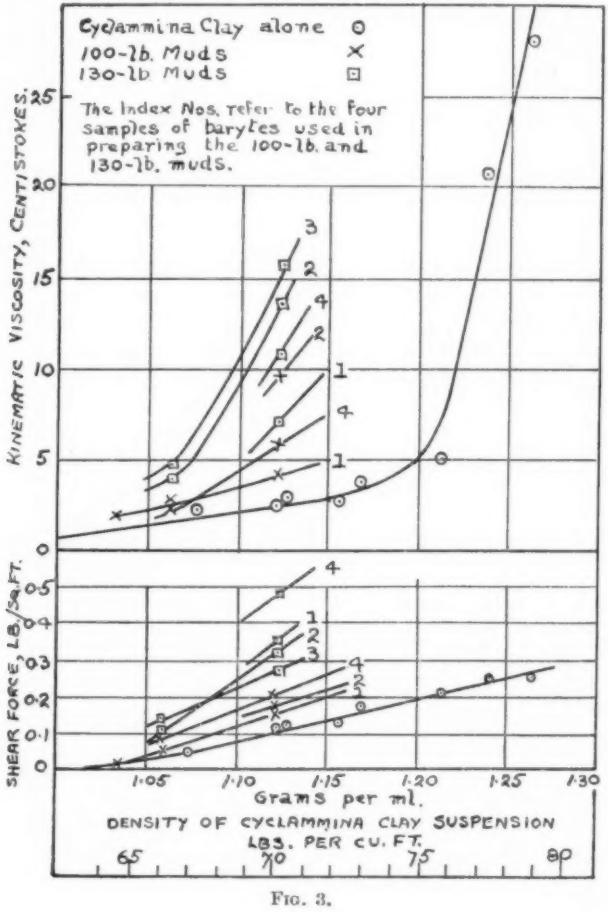
Cyclammina Clay alone ○
100-lb. Muds ×
130-lb Muds ⊡
The Index Nos. refer to the four samples of barytes used in preparing the 100-lb. and 130-lb. muds.
KINEMATIC VISCOSITY, CENTISTOKES.
SHEAR FORCE, LB./SQ.FT.
Grams per ml.
DENSITY OF CYCLAMMINA CLAY SUSPENSION
LBS. PER CU. FT.

FIG. 3.

Some muds in use on the field are too thick to be handled in 100-ml. cylinders. Such muds are, however, generally stable in regard to settling: which is chiefly in question with muds thin enough to test in this manner.

Regarding the instability of barytes-clay mixtures of too low a clay content, the colloid chemistry of such mixtures is of interest. Clay particles are negatively charged, while barium sulphate particles are positively charged, so that the two when mixed are mutually precipitant. Baver and Rehling[6] make use of this in soil analysis, by adding barium sulphate to clarify soil suspensions ; alkaline clays requiring more barium sulphate than acid clays. The coagulation effect from this cause is chiefly in evidence when the barytes particle is of colloidal dimensions. There is, therefore a limit to the desirable fineness of barytes for drilling muds. At the same time, the polarity of charge carried by a colloid particle is dependent upon the ions present in the menstruum ; by suitably adjusting these it may be possible to give both barytes and clay particles the same charge and thus ensure better stability.

Clays poor in colloidal characteristics may be compensated by the addition of aquagel or bentonite, a very highly colloidal form of clay. It is apparent from the foregoing, however, that the local Cyclammina clay is satisfactory in this respect, and that thin high-density muds of sufficient stability may be prepared with simple clay-barytes-water mixtures provided attention is paid to the clay concentration.

Penetration of Formation.

The mud should penetrate the formation as little as possible, in order to prevent clogging up of a productive sand, loss of mud, thickening of the mud due to filtration effects, etc. Parsons quotes some interesting experiments in this connection.[7] Mud at pressures up to 2000 lb. per sq. in. was pumped for 10 min. against formations of various textures—fine sand, coarse sand, fine gravel and coarse gravel.

Bentonite alone at 2 and 4 per cent. concentrations failed to effect a shut-off ; but at 6 per cent. concentration the sands were shut off.

El Paso clay mud at 75 lb. per cu. ft., also El Paso clay weighted with barytes to 97 lb. per cu. ft. were tried. Both sands were shut off within the pressure range 100–400 lb. per sq. in ; and the fine gravel at 1800–2000 lb. per sq. in. No shut-off was obtained with the coarse gravel.

An interesting point brought out in these experiments is that barytes greatly reduced the penetration of the particles into the formation. With El Paso clay alone the penetration was $3\frac{3}{8}$ in. and $5\frac{1}{2}$ in. in the fine and coarse sands respectively ; while with the barytes-clay mixture the penetration was only $\frac{1}{16}$ in. and

[6] Baver and Rehling, *Ind. Eng. Chem. Anal.*, 1930, **2**, 338.

[7] Parsons, " Rotary Mud Practice in Mid-Continent," *Oil & Gas J.*, June 9th, 1932, p. 69.

$1\frac{3}{8}$ in. respectively. Similarly the amount of leakage into the coarse gravel formation was much less when barytes was present.

The formations used were unconsolidated, *i.e.*, with voids inter-connecting. An easier shut-off would be obtained with consolidated formations.

Relative Significance of Shear Force and Viscosity.

It has been stated that the consistency of mud may be represented by two quantities ; shear force and viscosity. While this is not true with absolute precision, it is nevertheless a close approximation as shown by many graphs of the Fig. 2 type. The dotted portion in Fig. 2 indicates the small extent of the deviation.

In regard to separating gas from gas-cut mud a small bubble will rise to the surface of a true liquid of however high viscosity if sufficient time is allowed. The rate of rise of the bubble is governed by Stokes' Law. Where a shear force exists, however, there is a critical bubble size below which the buoyancy of the bubble fails to overcome the shear force. The calculated figures for 100-lb. mud are :—

Shear Force of Mud.	Critical Bubble Diameter.
0·1 lb. sq. ft.	0·072 in.
0·5 „	0·36 „
1·0 „	0·72 „

Agitation is necessary in order to break down the shear force and realise the buoyancy of the bubble. Similar remarks apply to the settling of cuttings. The advantage of a low shear-force mud is evident.

Regarding the circulation of mud in a well, viscosity affects the pressure drop only indirectly by affecting the Reynolds Stanton turbulence criterion. For instance, the pressure required to pump 100 brl. per hr. of fluid weighing 125 lb. per cu. ft. through 3600 ft. of 4-in. line is :—

18 lb. per sq. in. if viscosity is 5 centistokes, or 33 lb. per sq. in. if viscosity is 50 centistokes.

On the other hand, the pressure required to overcome shear force alone is :—

57 lb. per sq. in. if shear force is 0·2 lb. per sq. ft., or 570 lb. per sq. in. if shear force is 2·0 lb. per sq. ft.

It appears, therefore, that shear force is a more important factor than viscosity.

Similarly with the Schlumberger electrical coring apparatus, the electrode is weighted with a plummet and lowered by cable.

The latter presents a large shear area. Assuming the following conditions :—

Plummet weight, 180 kilos (400 lb.), sp. gr. 10. Surface area, 20 sq. ft.

Cable weight per linear ft. 0·25 lb., sp. gr. 1·6. Surface area per linear ft. 0·17 sq. ft.

In 120-lb. mud the plummet will have an effective weight of 323 lb. The cable will float, and in the case of 3600-ft. hole, will reduce the effective weight by 146 lb. to 177 lb. On the figures, assumed the area of 3600 ft. of cable and plummet will total 630 sq. ft. This area has to be sheared by a force of 177 lb., so that, unless the mud has a shear force of 0·28 lb. per sq. ft. or less, the 180-kilo plummet will fail to reach bottom. This demands a very thin mud. With a 400-kilo plummet the critical shear force is 0·83 lb. per sq. ft. The figures quoted are tentative only, but indicate the conditions necessary to ensure reaching hole bottom with Schlumberger. Part of the difficulty in reaching bottom with the plummet may have been due to settling out or gelling of the mud, giving a localised high shear-force mud ; but this should not occur with good mud.

It will be apparent from the foregoing that except for density, shear force is probably the most important characteristic of a mud. Viscosity is also significant, but its value is far less critical. Both factors may be measured as indicated earlier in this paper. Shear force alone is, however, determinable in a much simpler manner by an instrument which might be called a Shearometer. This, in its simplest form, consists of a rectangular strip of thin metal which is lowered vertically into the mud (Fig. 4). It sinks rapidly at first, but is pulled up by shear force. The strip is calibrated directly in lbs. sq. ft. shear force. If :—

b=breadth of strip in cm. ;
l=length of strip in cm. ;
W=weight of strip in grams ;
D=density of metal ; grams/ml. ;
d=density of mud ; grams/ml. ;
R=distance in cms. which strip sinks,

then the shear force in grams per sq. cm. is :—

$$\frac{W}{2bR} - \frac{Wd}{2blD}$$

or in lb. per sq. ft. :—

$$\frac{2{\cdot}04}{2}\left(\frac{W}{bR} - \frac{Wd}{blD}\right)$$

A modified form is shown in Fig. 5, consisting of a fin presenting surface area but of negligible thickness, weighted by a high density

(*e.g.*, lead) sinker. If calibrated for 110-lb. mud, the correction when used for 100-lb. or 120-lb. mud is negligible.

Results with a piece of tinplate are shown in Fig. 6. With thin muds the Shearometer sinks at an appreciable rate, but with thick mud it stays relatively stationary. The first reading obtainable is sufficiently correct, although graphical extrapolation as

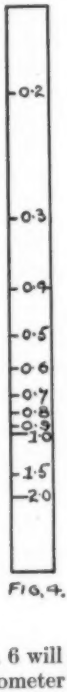

FIG. 4.

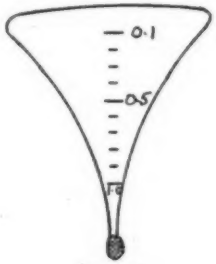

FIG. 5.

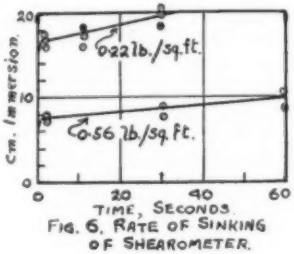

FIG. 6. RATE OF SINKING OF SHEAROMETER.

shown in Fig. 6 will give a more accurate figure. The slow sinking of the Shearometer corresponds with the dotted curved portion in Fig. 2, and is due to the fact that the shear force-viscosity concept is an approximation only, although a fairly close one.

It will be realised that this method of determination tallies closely with the lowering of the Schlumberger electrode, and may be of particular interest in this connection.

It is important to dry the Shearometer before every test, otherwise the mud becomes locally diluted and a low reading is obtained. The instrument has some advantages over the orifice type viscometer. The test causes minimum disturbance of the mud; so

that any tendency to gelling is revealed by testing at, say, hourly intervals.

Effect of Chemicals.

Sodium salts, such as silicate phosphate carbonate and hydroxide, are used for the purpose of "doping" muds. The alkalinity of these substances suggests that hydrogen-ion concentration is the important point. This is not the whole story, however, as the compounds have different effects. In plotting the effect of the chemical against the amount of chemical added, it is found that the curves are of widely differing shapes.

Sodium silicate is generally used to thin down a mud. It can, however, act in precisely the reverse manner. With some thick muds, the first portion of silicate added produces a still thicker mud, a gel; with increased amounts, the gel phase is transient or not observable and a much thinner mud results. The gel sometimes formed may be liquefied by agitation, but may re-form on standing in a matter of minutes or hours. With excess of silicate, clots become visible and a tendency to settling-out is manifest.

With other muds, no gelling tendency is apparent, and a much thinner mud is immediately produced.

Again, with still other samples of mud, silicate produces a gel at all reasonable concentrations. If, however, the mud is previously diluted with water, silicate does thin down the mud.

Probably the main factor responsible for this unsystematic behaviour is the clay concentration. The gelling is mostly manifested when the clay suspension carrying the barytes is 77–85 lb. per cu. ft. density or more. Reference to Fig. 3 will show that clay at this concentration is just on the steep portion of the viscosity curve, so that dilution with a little water would produce a quite fluid mud. The relative utility of silicate is therefore limited; it enables an additional mud density of about 5 lb. per cu. ft. to be obtained by clay instead of having to use barytes. Other factors which affect gelling are: the nature of the clay, its alkalinity or acidity, the amount of free carbon dioxide present, the amount and nature of the barytes present; the tendency of sodium silicate to peptize barytes, the presence of highly ionised salts such as sodium chloride, etc.

Sodium carbonate and hydroxide tend to thicken up a mud, but here again over limited ranges of concentration the effect may be to produce a thinner mud.

Excess of highly ionised salts tends to cause coagulation, probably by destroying the hydrophilic layer surrounding the clay particle.

Having regard to field operations and local conditions, the following comments may be made :—

(1) The amount of mud in circulation at the rig is not accurately known. As the consistency is changed by the addition of chemicals, the amount of stagnant mud in the pit also changes. The thickness of mud-cake on the wall of the hole, the penetration into the formation and associated filtration effects, may change. It is, therefore, a difficult matter to control the effective concentration of the chemical.

(2) In the presence of free carbon dioxide, sodium silicate is partially converted into sodium carbonate and free silicic acid. Both latter compounds cause gelling. The high pressure gas in the formation may contain 2—5 per cent. of free CO_2, so that its partial pressure in the reservoir may exceed one atmosphere. Assuming that the hydrostatic head of the mud is sufficient to prevent free mixing of gas and mud, there is still the possibility of slow diffusion of CO_2 into the mud, which might cause gradual gelling.

(3) A great deal of clay formation is encountered locally while drilling. This causes thickening of the mud. If silicate and water are used for thinning, then on further drilling the clay content may increase and form a much thicker gel than would be the case if no silicate had been added.

It is evident that the use of silicate for thinning muds is a speculative operation, and that laboratory results will not necessarily be reproduced on the field.

Towards the completion of a well thin high-density mud may be required, particularly for running the Schlumberger apparatus, and the absence of any gelling tendency is important. In this respect straight barytes-clay-water mixture can put up a guaranteed performance, but doped muds are less reliable.

Economic Considerations.

The main advantage of using silicate to thin down a mud is that a small quantity is effective, and the density of the mud is less reduced than if water were used. At the same time the economy in barytes is only a small percentage of the total barytes required for a well completion.

In drilling a well, the amount of clay encountered produces much more mud than is necessary for drilling operations. The reclaiming of this barytes should prove an economic cost in barytes. The reclaiming of this barytes should prove an economic practicability. As shown previously under the section headed "Stability,"

with a low clay content the barytes tends to settle out. By diluting the mud with water, therefore, with gentle agitation, most of the barytes settles out leaving the clay in suspension. By several such dilutions, it is possible to recover a reasonably thin 120-lb. mud from thick 90-lb. mud. The separation of cuttings, fine sand particles, etc., presents a more difficult problem however.

In the case of a compact field, the use of a central mud-preparing and reconditioning plant should appreciably reduce the outlay for barytes.

For a deep hole exploration the present type of Schlumberger apparatus requires a particularly thin mud; and a high density mud is necessitated by safety considerations. To thin down the mud sufficiently, and weight to 120 lb. per cu. ft. density, may require 50 tons or more of barytes.

A cable and plummet which would penetrate, say, 4000 ft. of mud of 1·0 lb. per sq. ft. shear force would be appreciably more economical.

DISCUSSION.

Mr. A. G. V. Berry said he would like to amplify what the author had said about the effect of sodium silicate on muds. He would quote an extract from a report dealing with laboratory work on the subject.

Sodium Silicate Solution.

Additions of varying amounts of this reagent up to 0·4 per cent. by volume to a mud showed practically no change in pH value, and these amounts had very little effect in improving "colloidity." Quantities up to 0·1 per cent. by volume of sodium silicate actually increased the rate of settling as compared with the original mud. The outstanding feature of the addition of sodium silicate to a mud is the resulting reduction in viscosity. This occurs only if the p_H value of the mud is above 7·0—i.e., in the alkaline condition, the effect in the acid condition being to cause thickening.

A freshly mixed Forest clay mud of sp. gr. 1·188 had an original pH value of 8·6. Portions were taken, and to each was added the same total volume of distilled water and a known amount of sodium silicate. The following results were obtained after 50 hrs.

Sodium Silicate Solution added.	Stormer Viscosity. Seconds.	pH Value.
Nil.	11·3	8·3
0·2% by vol.	9·3	8·4
0·4% by vol.	11·1	8·4

Samples containing 0·1 and 0·3 per cent. by volume of silicate were then made up. The viscosity of each sample was 11·4 secs.

about 1 hr. after mixing. After 14 days all samples were tested for viscosity and the following values were obtained :—

Silicate.	Viscosity Seconds.
Nil.	16·0
0·1% by vol.	13·2
0·2% by vol.	11·1
0·3% by vol.	13·1
0·4% by vol.	Insufficient for determination. About 15.

It will be observed that the pH value of the untreated mud dropped from 8·6 to 8·3 in 50 hrs. (The dilution with distilled water was insufficient to reduce the pH value appreciably.) The treated samples apparently dropped in pH value to a like extent. The minimum viscosity for this mud corresponded with the addition of 0·2 per cent. by volume of sodium silicate, and with all samples there was an increase in viscosity with age, but the minimum viscosity still corresponded with the same 0·2 per cent. by volume of sodium silicate after 14 days.

In order to confirm the above results, and to find the relation between specific gravity and the amount of silicate required for minimum viscosity, several litres of Forest clay mud with a pH of 8·4 were made up to a pH of 8·6+. Varying amounts of water and sodium silicate were added to give nine samples in three sets of three. The first three had a specific gravity of 1·207 and were treated with nil, 0·5 and 0·4 per cent. by volume of "S" brand sodium silicate. The second and third were treated with the same percentages of silicate, but had specific gravities of 1·178 and 1·119. The pH values taken 2½ days after mixing were all nearly the same, there being a slight variation of not more than from 8·6+ to 8·6–, i.e., a latitude of less than 0·1 pH. After correction for slight differences in specific gravity the samples all showed decreasing viscosity with increasing percentages of silicate.

It is evident that these muds at the higher pH require more sodium silicate to yield a minimum viscosity.

Mr. Berry also referred to the effect of protective colloids of the glue type.

Twenty samples of mud containing from 0·02 to 0·08 per cent. of glue, and varying in pH value from 6·0 to 9·0 were compared for amount of settling with an untreated mud of pH 8·1. The samples containing glue were in all cases inferior to the untreated sample of mud. Glue was also found not to be beneficial in reducing the deleterious effect of salt waters on drilling mud.

Mr. H. C. H. Darley said that he would like to take up the point of shear force and viscosity. The idea of muds having a yield point originated with Bingham and his supporters were

entirely American. The European investigators of gel-forming colloids of the type found in drilling muds did not agree at all with Bingham's results. Hatschek's work in particular was in marked disagreement. Their chief objection was that they found no yield point. Their graphs of viscosity against rate of shear showed a continuous curve passing through the origin and therefore no indication of yield point. This behaviour was natural in view of the fibrillar theory of gel formation. This stated that gels were formed by a fine mesh work of fibrils connecting the hydrated particles, and this imparted rigidity to a gel. With increasing rate of shear the fibrils were more and more broken up, and the viscosity fell off rapidly and continuously. He thought that the fibrillar theory explained all the properties of mud fluids, and the difference between their behaviour and that of true liquids.

Mr. M. A. ap. Rhys Pryce said he was interested in the results the author quoted from Parsons, who had done some experiments on drilling muds in the mid-continent. Parsons found an interesting thing with regard to adding aquagel or bentonite in drilling muds. He pumped mud into sand under a pressure of 2000 lb. pressure, and found that the addition of bentonite to mud at a small concentration of 2–4 per cent. failed to effect a shut off and with 6 per cent. an effective shut off was obtained. Mr. Rhys Pryce was indirectly connected with somewhat similar experiments. These experiments went a little further than those of Parsons and found some curious results, which were that with small concentrations of aquagel the viscosity of the mud actually decreased, whereas with larger percentages of aquagel the viscosity increased, which may explain the results that Parsons obtained. He did not know if anyone could explain it, but it seemed to be a fact that if one added too small a quantity of aquagel in mud, it was liable to decrease its viscosity instead of increasing it.

Mr. E. Cooper Scott said that he was very interested to hear of the results on shutting off by addition of colloids in the mud. He would like to give some account of a well that they had just lately had at Guayaguayare. These results showed a rather curious state of affairs with regard to the weighting of mud. They drilled through the upper sandy series with mud of 70–80 lb. weight, which was not absorbed into the formation. Below this sandy series they expected to encounter a clay series with oilsand under considerable pressure, and they put in about 108-lb. or 110-lb. mud, and that mud disappeared down the hole so fast that a cavity was suspected. They knew that geologically no such cavity should occur, and somewhat the same state of affairs occurred in a neighbouring well, but there it was not so pronounced. They

were able to keep mud of 106 lb. weight in the hole, but if they increased the weight it would disappear into the formation. He should like to ask the Author if he had any ideas as to what that condition could be. This was a case of a mud of very good colloidity, there was not a lot of sand in it, and yet it seemed to go into the formation as if there was no resistance to it at all.

Another point raised in the paper on which he should like to ask a question is the treatment of mud from wells. There seemed to be a variation of opinion as to what the object of such treatment was. Was it to recover the barytes or to make a sufficiently good heavy mud to drill with and, was it necessary in that case, to extract the sand ? He knew that that varied a great deal with the terrain, but he would like particularly the opinion of those who were drilling in very sandy strata as to whether it was necessary to remove the sand from heavy mineral laden mud or if it was only necessary to take out such clay cuttings as lightened the mud and to replace them with a certain amount of barytes. On that point, he thought, hinged the whole idea as to what was the object in treating mud. He rather fancied that sand was the content that they must try to eliminate, because he thought that additional clay with the aid of extra barytes would make a sufficiently good drilling mud and thus all barytes used would remain in the circuit. If the content was too sandy, they must use some sort of classifier to remove that sand, and he rather wondered whether the point mentioned, that it was difficult to remove sand, was in fact so, or whether it was not just a question of adequate dilution with water so that the relatively large sand grains could be segregated.

Mr. A. Frank Dabell said that the study of drilling mud generally was of increasing interest, and he felt that they should welcome all the papers that could be obtained on the subject.

Within recent years mud was credited with being the agent responsible for most of the failure associated with subsequent production of drilled wells, but it was now being accorded some degree of virtue, and it was obvious that the chemist was contributing valuable aid to operators.

Dealing with the use of mud, he welcomed the declaration that experiment with barytes-laden mud showed that barytes reduced penetration of the particles into the formation. In all reason why should barytes be expected to go further into the rock ? It could not be of finer grain than the clay particles it is mixed with, and yet critics of the use of barytes condemn it on the ground that it is bailed from wells many months after they are brought into production. In fact, barytes merely permitted recognition of the mud that went into the well originally—no more, nor less.

The passage of time tends to confirm the declaration of H. Anderson, made as far back as 1922, that "mud deposited upon the surface of the hole wall is quite permanent as long as the hydrostatic pressure on the fluid in the hole exceeds the rock pressure of the fluids—water, oil and gas being mudded off. The deposit, however, offers no resistance to being backed out of the formation as soon as the rock pressure exceeds the hydrostatic pressure in the hole. The deposit acts only as a sheath held in place by the hydrostatic pressure in the hole.

"The speed of the 'mudding off' process is practically instantaneous."

Of current interest is the propaganda in favour of the use of underreamers as wall scrapers for the removal of the mud sheath, the idea being that by their use the wall of the hole is left clean for release of the rock content. This practice might be applied with advantage to low-pressure shallow wells, but with deep rotary drilled wells if the contention put forward by Anderson is accepted, then immediately following the operation the well is plastered and sealed instantaneously so far as porous rock is concerned.

Col. H. C. B. Hickling said the paper would have been interesting to the many field staff present who did not use a laboratory viscometer in the field if the Author had given them some means of recognising the fluids he talked about. They knew the weights of the Cyclammina clay, but a few comparative figures on a field viscometer would have enabled them to recognise their friends and follow the paper a great deal better.

The point about the Shearometer that appealed to him was that if it could be used in the field it appeared to be in some ways simpler than the field viscometer, although as he understood it, when measuring shear the readings that one obtained appeared to be much smaller than the readings obtained from viscosity. The benefit would therefore appear to cancel out, because viscosity gave differences of five times the magnitude of the shear differences which would make them very much easier to read. He would like the Author to tell them something about that.

The recovering or re-conditioning of barytes mud was a commercial subject into which the cost of barytes, cost of mud, and a great many other things entered as to whether it was a paying proposition to put in a mud-treating plant. The plant that had appealed to him was one on the Ventura field, but he understood that clay there was very expensive. Where clay did not cost much, it might be a different proposition. He did not see any difficulty if it was a paying proposition.

It was an old problem and, since the Dorr firm had used concentration methods, it had become simple. He thought that the separation of fine as opposed to coarse sand particles was the more difficult problem. Once the mud was sufficiently diluted, the coarse sand would come down with the barytes and then, of course, it was a matter of screening. Ample dilution got rid of gas and oil and settling, screening and thickening completed the process.

Mr. G. W. Halse said that the Author had raised a point, also touched on by Mr. Dabell, concerning the liability of drilling mud to filtration. He had often wondered how far the water, which was seen in cores, might be water filtered from the drilling mud. A case in point was the definite appearance of water in cores in some wells in Venezuela at horizons where it was highly improbable that there would be water. It might be thought that this could be resolved at once by salinity tests. In this region, however, the connate waters ran about 53 parts of salt per 100,000, which is so fresh that it is impossible to be certain from salinity tests whether such waters were indigenous or not.

To make quite sure whether the drilling mud might have been the source of the water, lumps of the sand from the cores were dried for several hours at 100° C., and then placed in the drilling mud, which was pumped up to a pressure of 1000 lb. per sq. in. After a few minutes the pressure was released and the muddy outside of the core removed. It was then found that clear water had penetrated to the interior of the sand.

The cost of barytes was drawing attention more and more in Trinidad to the possibilities of recovering barytes from discarded mud or else of re-conditioning the mud to make it fit for use again. One stage in the process was the elimination of sand. Experiments conducted at Palo Seco (Trinidad) had shown that in 3500 ft. wells the amount of sand in the mud delivered from the pumps which would not pass a 90-mesh sieve amounted to only 0·06 per cent. by weight, and furthermore that this amount remained approximately constant throughout the drilling of the wells. Some of the fine sands and silts in the formations drilled through would undoubtedly pass through a 90-mesh sieve, but the producing sands, amounting to an aggregate thickness of 100 to 200 ft., certainly would not do so. Further investigation would, therefore, be necessary in order to explain this surprisingly small amount of sand.

Mr. J. L. Harris said he was of the opinion that there was a great deal more to be learnt about this very important subject, and that without any detrimental criticism of the paper he held

that this was one of the many subjects in which the one-eyed was king of the blind.

Other members had criticised the fundamental points of the paper, and there was only a few matters on which he would ask for information.

First, with regard to the wettability of the mineral barytes, he was of the opinion that this factor was probably due to chemical impurity. Barytes was a very stable mineral and exhibited definite characteristics, and he was still convinced, in spite of the Author's remarks, that the specific gravity was the criterion, and probably the only criterion, in assessing the value of the mineral for making heavy muds.

Second, he was very interested in the Author's views for getting the plummet of the electrical coring apparatus to the bottom of the hole. His experience indicated that circulation for a considerable time, say, 6–12 hrs., was a great help. The viscosity was reduced appreciably by such procedure, and often the plummet reached bottom when the mud was of a very high viscosity (over 50 secs.). The uniformity of the mud attained by circulating seemed as valuable as a low viscosity.

Third, the use of barytes and water mixtures would seem to be expensive as well as risky, and in the best circumstances only a short period of time would elapse before mud got into the mixture, i.e., from sides of hole or by new drilling.

Fourth, the recovery of barytes was an important matter as the cost of the mineral used in a well was at least £200–£300 and might be ten times the amount.

It was not a question of recovering this barytes in the solid mineral form (pure and unadulterated).

It was sufficient, he submitted, to produce a 90–110 lb. mud from the original gas cut fluid, and to have suitable arrangements for storing the recovered heavy mud till it was desired to use it.

The problem was not similar to the dressing of a mineral ore, though superficially there seemed to be some points of resemblance.

Mr. A. J. Ruthven-Murray mentioned that when drilling on their particular structure, the Vance River anticline, their main trouble was excess of clay shale, for it was found that the mud rapidly became viscous on this account, and in order to maintain the required weight and viscosity it was necessary constantly to pump away a proportion of the drilling mud and build up the remainder by the addition of water and fresh barytes. He felt that a barytes separation plant in that particular area would be valuable for eradicating the excess clay shale from the barytes, and, of course, all mud should be passed through a vibrating

screen, preferably installed at the well, to separate sand and lumps of clay shale.

With regard to the running of the electrical coring device, they found in one well that the mud was too viscous for the plummet to sink satisfactorily, and in this case they had to build up a fresh supply of mud with barytes to 110 lb., using 72 lb. shale mud as a base and adding sodium silicate: the original mud in the well weighed 110 lb., but had a high viscosity on account of excessive shale. The main point of importance when drilling in shale formation was to keep the weight of the base mud around 72 lb. to 75 lb. and then build up on that with barytes. That sand undoubtedly did harm was evidenced by the fact that the eyes of the bit became severely cut, and that surely indicated that sand should be freed from the mud at all times.

Gas pressures encountered on the Vance River structure made it necessary to expend on an average $5,000·00 for barytes per well.

The Chairman, Mr. G. H. Scott, said that he rather took issue with the author as to the actual measurement of viscosity by a Stormer viscometer. He thought that accurate results could be obtained if the observations were made with a constant rate of shear. The instrument used in this manner was perhaps the most practical method for determining mud viscosities in the laboratory.

With regard to the stability of barytes clay muds, the Author had stated that barytes and clay particles were mutually precipitant, yet the results of his tests showed that an increase of the clay content of a mud tends to inhibit the settling of barytes.

He thought it was now generally agreed that the stability of a clay suspension was not caused by suspensoids of colloidal dimensions but to emulsoids or, as they were termed, "gel forming colloids." He would refer the Author to Alexander on "Colloidal Chemistry" and Cushman's "Effect of Water on Rock Powders," where it would be seen that the actual colloidal portion of a clay formed a very small proportion of the whole.

This conception of clay suspensions would explain the marked increase in viscosity with increase in the quantity of the disperse phase. In the case of true suspensoids, as in the case of crystalloidal solutions, the variations in the viscosity were more or less proportional to the weight of the disperse phase. In the case of emulsoids, however, the viscosity increased mud more rapidly than did the weight of the disperse phase. Thus the form of the viscosity specific gravity curve gave a valuable indication of the proportion of the gel forming colloids in a clay.

The other point in which he disagreed with the Author was his differentiation between viscosity and shear force. Viscosity was

itself that physical property which caused a fluid to offer a resistance to the relative sliding motion between the adjacent particles. In his opinion this was entirely dependent on shear force, in other words one could not differentiate between shear force and viscosity, they were one and the same thing.

In the matter of yield point, which was dilated upon by Mr. Darley, he agreed that the viscosity decreased markedly with an increase in the rate of shear, but Hatschek and Anderson disagreed that there was a true yield point, and stated that if sufficient intermediate observations were made there was no definite break in the curve, it was purely hyperbolic.

The passage of mud through a hopper for degassing purposes provided a very fine illustration of the reduction of viscosity by an increase in the rate of shear, and it was very probable that any degassing that did occur was facilitated by and resultant on this reduction.

It was always brought up that the question of the colloidal content of the clay was purely of academic interest. In reality, on the colloidal content of a clay depends the stability of the mud, its behaviour in the presence of electrolytes, the viscosity of the mud, its formation sealing properties and its resistance to coagulation in the presence of saline waters.

He quite agreed that it was very difficult to devise an ideal drilling mud for all drilling problems. When drilling through an oil sand series a somewhat viscous mud was probably required so as to give the quickest sealing effect, but this in its turn would increase the settling out of cuttings. For normal drilling a very fluid mud was indicated, but this might set up caving or allow of barytes settlement. Similarly in regions of high gas pressure, while a heavy viscous mud became easily gas cut, reduction of viscosity by the addition of electrolytes might well set up frothing as a result of a lowering of surface tension so that it was possible that while the reduction of viscosity might aid in the liberation of gas, the lowered surface tension might tend to aggravate gas cutting subsequently.

Even when one had obtained the ideal mud for any one drilling condition, as Mr. Dabell pointed out, it was very liable to change with service as a result of syneresis, and consequent hardening and breaking down of the colloidal gel structure, as a result of contamination by the formations traversed, of the pecktizing action of saline waters and by true adsorption of gaseous hydrocarbons.

It might be necessary in the future to vary the colloidal content of a mud to meet varying conditions, and it was this phase of mud control which called for careful chemical investigation.

Mr. L. A. Bushe said that he was interested in the question of sand content in the mud. To the man actually operating the pumps and other equipment, he thought that the sand content was very important, and he should like to hear other views on the maximum sand content which one should allow in a drilling mud. They had on the Apex Fields at various depths sand content ranging from 5 to 35 per cent. by volume. He could not say, in spite of fairly close records, that the 35 per cent. sand had caused a great deal of wear to the equipment, but there was no doubt at all that if the mud was to be reconditioned the sand should be eliminated. He would be glad if the Author could help them by explaining the question raised by Mr. Halse as to what happened to the sand.

Mr. P. Meyer, in reply, said that he was interested in the figures produced by Mr. Berry in regard to the effect of pH on the action of silicate. On the field, pH control might be a matter of difficulty, however, particularly where the formational gas contained CO_2 and the mud was sensitive to small pH changes. The clay density might also be a factor influencing the effect of silicate. Mr. Berry's conclusions were based on a 74-lb. mud which apparently contained no barytes; the Author felt that with a mud of higher clay content containing barytes, quite different conclusions might be drawn. In the Author's experience, thick fields 90–120-lb. muds, requiring thinning to suit the plummet of the electrical coring device, became still thicker on the addition of reasonable amounts of silicate. It should be observed that sodium silicate is no simple chemical compound, and may vary in composition and in effect produced.

Replying to Mr. Darley and the Chairman, he fully agreed that the viscosity-shear force concept was an approximation only. He had been at pains to state that several times in the paper. He quoted Herrick because Herrick had dealt specifically with the mechanical flow of drilling muds, and not with fundamental issues. References to both Bingham and Hatscheck would be found in the article by Herrick.

He agreed that the factors referred to as shear force and viscosity were both in the nature of internal friction. At the same time viscosity was normally regarded as a physical constant for a given liquid, dependent only upon temperature. That would not be the case with plastic solids.*

* Author's Note.—An interesting contribution to the subject was "Investigations into the Plastic Properties of Asphaltic Bitumen," by Saal and Koens, *J. Inst. Petr. Techn.*, 1933, **19**, 176–212.

The problem which confronted him was, given a sample of mud, how to predict its suitability for circulating in a well, and for lowering the electrode of the electrical coring device ? He was looking for a calculus which systematized the experimental facts of mud flow. The experimental results were of the type shown in Fig. 2. In this figure, as in Fig. 6, the continuous nature of the flow curve referred to by Messrs. Darley and Scott had been clearly indicated. It happened, however, that a well-defined change of slope was observed with drilling muds, and that the flow curve in Fig. 2 could be represented with fair accuracy by two straight lines. The significant fact was that the flow rates below the change of slope were so slow as to be without practical significance ; in other words, the asymptotic portion of the curve was for practical purposes coincident with the horizontal axis.

He could assure the speakers that such was the case experimentally for drilling muds, although of course for other colloidal systems the approximation might be less accurate.

If either Messrs. Scott or Darley could advance a mathematical theory of mud flow involving a single constant instead of the two utilised in this paper, he would welcome it. Failing such a formula, however, the shear force viscosity combination did provide a simple calculus ; he would, however, add that he did not know to what extent the applicability of the Reynolds-Stanton criterion had been established for the flow of plastic solids.

Mr. Rhys Pryce had contributed some further interesting facts in regard to the effect of bentonite, and on penetration of the formation.

Many speakers had referred to the significance of sand in a mud. The degree of abrasion of pump liners was probably a function of particle size ; possibly the smaller particles were relatively inoffensive. A combination of dilution settling and/or screening was certainly a promising line. It was evident that field conditions differed considerably in different localities on the island. The conditions indicated by Mr. Ruthven Murray, that was a tendency to accumulate excess of clay and to find no trouble with sand, were much more familiar to him than those referred to by Mr. Bushe, Mr. Cooper Scott, and others.

With regard to mud baled out of a well some months after the well had been producing, he agreed with Mr. Dabell that the presence of barytes was generally clear proof that the mud was originally drilling mud. If plain unweighted mud had been used in drilling the well, the origin of the mud balings was less demonstrable.

Replying to Colonel Hickling, the Author thought that as a robust instrument giving an approximate differentiation between

thick and thin muds, the Trinidad Institution of Petroleum Technologists' viscometer* was undoubtedly of use. A correlation between the viscometer flow times and shear-force-viscosity values could be worked out. Regarding the significance of the readings, in some cases with thick muds the hydrostatic head of the Trinidad Institution of Petroleum Technologists' viscometer was not far removed from the zero flow head. Consequently two muds possessing only a slight difference in shear force might show a large difference in apparent viscosity by the Trinidad I.P.T. or other type viscometer.

Mr. Halse had commented on the fact that the sand content of a mud did not rise as much as might be expected when drilling through a sandy formation. The Author said that he had no experimental evidence to explain the matter.

Mr. Harris had referred to the subject of the " wettability " of barytes. He could assure Mr. Harris that it was an important point. Regarding the procedure for mud conditioning for the electrical coring apparatus, the Author said that the conditioning of mud after the well had been drilled into a high-pressure formation was, in the field with which he was best acquainted, a routine matter. It was usual to add small quantities of barytes and water alternately, until a thin mud of high density had been built up. Continued circulation to homogenize the mud was entailed by this procedure.

Several speakers had referred to the subject of barytes recovery or mud reconditioning. The feasibility of the process was naturally dependent on field conditions. Instead of adjusting mud for the plummet of the electrical coring device by adding barytes and water separately, the two could be added together in the form of a slurry. In that case it might pay to wash out the excess clay from discarded thick muds and aim at the recovery of a barytes-water slurry for the purpose, instead of using fresh barytes. The slurry would still, of course, contain some clay; complete removal of the clay was neither feasible nor desirable.

Replying to the Chairman, he thought that a graph of the Fig. 2 type afforded much more useful information than did a single viscometer reading. A series of readings by the Stormer viscometer would give the necessary data; but he did not think that a single reading was very informative. The results shown in Fig. 6 had an obvious and direct bearing upon the lowering

* AUTHOR'S NOTE.—The Trinidad Institution of Petroleum Technologists' viscometer consists of a cylindrical vessel 12 in. high by 8 in. diameter, carrying on the underside a vertical capillary 3 in. long by 7/32 in. diameter. The viscometer is filled with mud and the time of outflow of 700 ml. of mud is recorded as the viscosity.

of the Schlumberger plummet, and constituted a simple and rapid test applicable in the Field.

Regarding the mutually precipitant effect of barytes and clay, he thought that a thin clay suspension to which barytes had been added was more prone to settling-out than was the original clay suspension. Other factors might, of course, be operative in this connection, but the reference quoted in the bibliography was of interest.

The Author hoped that the importance of colloidity in clay or mud had been given due significance in his paper, and agreed that a great deal more research was necessary to clear up a number of points.

On the motion of the Chairman a vote of thanks was accorded to the Author, and their hosts, the President and Members of the Apex Club, for the use of the building.

Liners, Perforated and Screen Pipe.

By Albert Millar, A.M.I.Mech.E. (Member).

In the early days of oilwell drilling operators were faced with the necessity of finding means to support that portion of the borehole penetrating the producing sand or sands against caving. In course of time the liner was adopted in the form of a screen to restrain loose and free sands from entering a well.

A great deal of attention has been paid to the design and perfecting of perforated casing and screen pipe during course of development, very ingeniously designed tools have been constructed for cutting the slots.

Functions of a Liner.—The primary function of a liner, either as an integral part of the oil string or as a separate unit, is to support the walls of that section of the borehole penetrating the gas and oil producing formation. By preventing caving, an open hole is maintained.

Its secondary function is to act as a screen where the producing sand is fine and loosely cemented, or is in more or less a free running state. It will hold back the fine particles of sand, thereby counteracting wholesale disintegration of the producing sand and consequent plugging of the borehole by " cavings."

Types of Screen and Perforated Pipe.

Wire Wound Screen Pipe.—The pipe is first perforated with holes $\frac{3}{8}$ in. to $\frac{3}{4}$ in. diameter, depending on the size of the pipe, the holes being spaced on 1 in. centres or more. The pipe is wrapped externally with special wire having a " V " or " T " shape, leaving a nominal space between each wrap. The screen thus formed allows the fluid and gas to flow through the perforations whilst holding sand and other matter in check. The space between each wrap of wire is measured in fractions of an inch, screen pipe of this kind being obtainable with width of screen space from 0·005 in. up to 0·2 in. and larger.

This type of screen is very effective, especially when dealing with very fine sand and silts which will pass through a sieve with a mesh of 60 and finer. As the total area of screen space per lineal foot of pipe is considerable, resistance to flow is comparatively low ; further, owing to the spiral form of the screen the flow space is equally divided over the entire surface of the pipe.

There are, however, disadvantages, the chief of these being its inherent weakness to withstand even average handling during transport and around the derricks, especially when lowering into or withdrawing from a well. To be effective the wire wrapping must not become damaged or displaced, otherwise some of the

openings will be completely closed and others opened up to double or treble their original size, thereby greatly impairing the screen's efficacy. Moreover, the pipe will be cut away by the sand blast action of the sand which the damaged screen wire is incapable of holding in check, within a short space of time the screen as such becomes useless.

It is impossible to run wrapped screen pipe into a hole which is kinked, corkscrewed, or badly out of the vertical without risk of damage. If a hole is not in perfect order, it is advisable to run a smaller size screen pipe than would be used under normal conditions.

It is difficult to free and pull a string of wrapped screen pipe without damage, even where " washing " over is resorted to, trouble is generally caused by the wrapping wire getting loose and " wadding " up behind the pipe.

In spite of its weak points one must admit this type of pipe is very effective when dealing with acute sand conditions, provided every possible precaution is taken whilst it is being transported and being run into the hole.

Tests with Wire Wound Screen Pipe.—Some interesting tests have been carried out by Mr. A. E. Carr with this type of pipe. These tests were reported in the A.P.I. Bulletin No. 2, 1929.

2. *Button Type Screen Pipe.*—This type of screen is manufactured by drilling $\frac{5}{8}$ in. to $1\frac{1}{8}$ in. or larger diameter holes, depending on the circumference of the pipe. Metal buttons with slotted perforations varying from 0·008 in. to 0·150 in. are then pressed or screwed into the apertures.

Button screen pipe was an improvement on wire wound screen pipe, as there is less chance of the screen openings sustaining damage during running in. It can be run into a tighter hole than wire wrapped pipe, and can be lowered through kinked or other deformed sections of the well, provided it is not unduly forced. Another point in favour of button screen pipe is that it is more easily pulled free and washing over is facilitated.

Its chief disadvantages are :—

(*a*) That the total area of screen opening per sq. ft. of pipe is smaller than that obtainable with wire wrapped pipe.

(*b*) Owing to the spacing of the buttons the screen is not as continuous and a good deal of blank pipe faces the producing sand.

3. *Slotted Screen Pipe.*—This type has many advantages over wire wound and button screen pipe, both of which it was anticipated to supersede.

The slots are generally " V " shape, the apex of the " V " being to the outside of the pipe. These slots are mostly cut parallel

with the axis or around the circumference, and arranged either singly or in groups of three or four and sometimes more. The number of single slots or groups of slots per sq. ft. of pipe depends on the pipe's diameter.

Its superiority lies in the fact that there are no wrappings liable to displacement and damage, nor buttons to be dislodged, and it will stand a fair amount of hard usage.

Pipe should never be used which has become dented at a point of perforation or which has had its shape altered after the slots have been cut. Since two-thousandths of an inch mean a great deal in screen efficiency, it will be seen that even this type of pipe requires careful handling at the surface as well as during lowering into a well and setting.

The necessity for careful handling is not always appreciated and pipe is sometimes run with distorted slots. The author has witnessed slotted pipe extracted from wells with the slots so badly worn by abrasion that it had no longer fulfilled its purpose as a screen. It was possible to insert all one's fingers into a slot which had been originally 0·01 in. wide. In some cases only one or two groups in a 20 ft. length of pipe were so eroded ; this would indicate that original local damage (probably at the surface) was the cause of the trouble. One or two oversized slots in a joint of pipe would pass sand which would tend to rapid wearing away through abrasion.

4. *Plain Perforated Pipe.*—Standard pipe is used for this. The screen is formed by perforating the surface with a number of round holes varying from 1/16th to $\frac{3}{4}$ in. in diameter. The number of holes per foot of pipe may be from 8 to 380, depending on size of hole and diameter of the pipe.

This pipe is not suitable to hold back fine sands and silts where " fines " which will pass a 60 mesh are in the majority. 1/16th in. equals 0·0625 in., and for a screen to be effective the width of its openings must not exceed 0·010 in. All depends on the type of sand being dealt with, whether it be fairly compact, loose or crumbly, what sized perforations should be used.

Wherever it is possible to hold the sand " in situ " with plain perforated pipe, this type should be used as it possesses many advantages over wire wound, button screen or slotted screen pipe. These advantages being :—

(*a*) Better distribution of perforations than is possible with either the button or plain slotted types.
(*b*) Smaller area of blank pipe faces the sand.
(*c*) As compared with slotted pipe, round holes will remain open and effective much longer than will slots, even where clay is present.

(*d*) The chief advantage lies in the fact that round holes are not adversely affected to anything like the same extent as slots ; the round hole presents a considerably smaller surface to sand abrasion than a slot with the same area of opening, for instance :—

SLOTS PER FT. LENGTH.

No. of slots.	Width of slots.	Total slot area.	Exposed surface or rim to abrasion.
20 per ft.	0·010 × 4 in. long.	0·800 sq. in.	20 × 8 = 160 sq. in.

HOLES PER FT. LENGTH.

No. of holes.	Diameter.	Total hole area.	Exposed surface or rim to abrasion.
300 per ft.	$\frac{1}{16}$ in.	0·921 sq. in.	0·1964 × 300 = 58·9 sq. in.

This type of screen has the disadvantage that it cannot be used to hold fine sands and silts in check.

Plain perforated pipe is more robust and is not as likely to be affected by local denting, kinking or distortion in some other manner.

It can be used with advantage where trouble is experienced with crumbly, lightly cemented sand, provided a fairly large percentage of coarse sand grains is present ; these will in time build up a natural filter by bridging the perforations.

How many perforations of a given size should there be per unit area of pipe ? is a question frequently asked. It is difficult to reply, as conditions may vary considerably, but it would seem advisable to put in the maximum number of holes taking into consideration the strength of the pipe.

1. *Selection of the Type of Perforated Pipe or Screen.*—Before deciding on which type of screen to use and the number of slots or perforations best suited to prevailing conditions, details of well and the sand formation must be known :—

(*a*) Depth of well.
(*b*) Total thickness of gas/oil bearing sand or sands.
(*c*) Position and thickness of interbedded strata.
(*d*) Texture of sand throughout its entire depth.
(*e*) Nature and texture of interbedded strata.
(*f*) Bottom of hole temperature and pressure.
(*g*) Gas/oil ratio.

Coring is undoubtedly the most reliable means of obtaining accurate information, and it is excellent practice to core the rocks comprising the production series, and a complete log should be kept of the formation passed through just prior to entering the gas/oil bearing sand or sands, as well as of interbedded strata where these occur. Cores afford not only a correct stratagraphical

picture of the formation penetrated by the drill, but also show the texture, porosity and saturation of the sand.

It is known that sands differ considerably in their texture over comparatively small areas and depths. Knowledge of such variability may not only have a definite bearing on the productivity of individual wells, but will prove of valuable assistance when determining the type and size of screen perforations to be adopted.

For example, texture of sand may vary perceptably where the sand body is of notable thickness or is composed of a number of sands separated by layers of silts, clays or shales. Whereas one size and type of perforation may suit the requirements of a particular sand formation, it may easily prove quite unsuitable to another sand located a few feet deeper. When the exact thickness of interbedded strata is known, it can be blanked off by using full pipe.

Until recently, gaps occurring in core recovery had to be filled in from driller's information, which proved as a rule a most unreliable source. In order to fill in the gaps where core recovery or the condition of the cores has been poor and to check up information deduced, the electrical log method can be used with advantage in combination with continuous mechanical coring. The "Restivity" and "Porosity" logs are most valuable, since they enable an idea to be formed of the disposition of the sands containing chiefly gas, although in some cases very light oil-bearing sands will log in a similar manner to gas-bearing sands. Certain sand core samples may indicate that little oil or gas is present, yet the electrical method will log this same formation as being highly saturated and therefore well worth while testing out.

This diversity can be explained. Cores recovered from a sand several thousand feet deep may have been highly saturated "in situ." By the time these cores reach the surface most of the oil and gas originally contained in these specimens will have left them, due to the different pressure conditions existing at the bottom of the hole and the derrick floor. The lighter the oil, the more gas there is both in and out of solution, and more intense will be the weathering likely to take place.

Correlation of the characteristics of the electrical log with actual core samples and production results will have a direct bearing on determining the rate at which production can be taken from the sand without causing disintegration or caving or possible gas locking in the sand adjacent to the well due to too high a pressure differential being set up in the sand. No difficulty will be met in determining the right type of perforated pipe or screen and size and number of perforations after studying the cores and logs.

In some fields the electrical method has already superseded mechanical coring for correlation purposes in the upper section of the hole. By taking full advantage of the electrical method, a large percentage of mechanical coring for correlation purposes can be disposed with. Nevertheless, the use of both methods is strongly advocated, as soon as the hole approaches to within 100 to 200 ft. of the anticipated productive zone.

Selection of Oil String or Liner.

The selection of a suitable liner offers no special difficulty where the sand from which production is derived is of a well cemented and compact nature and not inclined to erosion or disintegration. The purpose of the pipe is to protect the hole from fragments of falling sandstone.

Size of perforation does not play a major rôle as long as the holes are kept within certain limits. Smaller diameter holes more closely spaced are always to be preferred to a few more widely spaced larger sized holes. A good average would be 60–72 $\frac{3}{8}$ in. holes or more per foot length of pipe according to the pipe's circumference.

A. Under certain conditions, sand or sands which appear to be well cemented, are prone to disintegration if a large volume of oil and gas is produced per unit area of producing face of sand, combined with a high pressure differential across the face of the sand adjacent to the hole. In such case it would be advisable to use smaller perforations—3/16th or $\frac{1}{4}$ in.

B. Where the sand is of a soft nature composed mainly of large sand grains which will not pass a 28 mesh, perforated pipe might be used with advantage if 120–160 3/16th in. holes are allowed per foot of pipe.

C. Where the sand is of a soft nature but contains a fair percentage of fine grains which will pass a 40 mesh with at least 20 per cent. which will not do so, 250 to 360 3/32 in. or $\frac{1}{8}$ in. dia. holes per foot of pipe would be preferred. This is to be recommended if a large volume of oil and gas is to be produced per unit area of exposed face of sand.

D. If the sand is soft and crumbly with a large percentage of "fines" (30 to 50 per cent.) which would pass a 60 mesh, slotted or wire-wound pipe should be used with a slot opening of 0·02 in.

E. Where, in addition to being soft and crumbly, the sand contains silts as well as a fair percentage of fine grains, slotted or wire-wound pipe with a slot or opening width of 0·01 in. or 0·015 in. would be found suitable in most cases.

F. When the sands are loose and contain a large percentage of very fine grains with not more than 15–20 per cent. of larger grains

which will not pass a 48 mesh, the slot or opening width should be approx. 0·008 in. to 0·010 in.

It is of paramount importance that the openings in the liner should afford the maximum flow area per unit length of pipe. To ensure this, the diameter of the holes should not be enlarged, but the number of holes should be increased.

Another point to remember is that the total number of slots or holes governs the velocity through individual apertures, and velocity has a direct influence on the production of sand with the oil. The part velocity plays in sand disturbance on the outside of the screen and the movement through the screen itself cannot be over-estimated. Velocity has proved to be one of the chief causes of abrasion; it is therefore most desirable to keep the velocity of oil and gas passing through the screen at the minimum.

In the event of a number of slots or holes becoming plugged and consequently non-operative, additional work will be thrown on those remaining open. Where a screen has ample screen opening area, the efficiency will not be thereby diminished to any appreciable extent. Conversely, where the screen opening is limited, plugging of even a small percentage of the holes may result in rapid cutting out of others due to the increased velocity.

As the larger grains of sand accumulate and build up a natural filter, so the pressure drop across the liner or screen pipe will increase, and continue to increase as the finer grains of sand build up behind the larger ones. This pressure drop will be more pronounced where the minimum number of slots or perforations exist per unit length of pipe as compared with the maximum number for a like area.

Viscosity of Oil—Screen Openings.

Viscosity of oil has to be taken into account when determining type and size of screen best suited to prevailing conditions. Lighter grades of oil with low viscosity will not adversely affect the screen to the same extent as would a heavy and viscous oil under certain conditions. Conditions existing at the bottom of the borehole, such as temperature, pressure and gas in solution, should be taken into consideration in connection with screen flow efficiency where a viscous crude has to be produced. The viscosity of a crude as taken from a lease tank is no criterion of its viscosity when emerging from the sand. The temperature at the sand face will vary with the rate of production, and gas expansion alters considerably during the life of a well.

Gas in solution is an important factor. The amount carried by the oil depends on pressure, and the percentage of different hydrocarbon fractions forming the gas as well as the composition

of the oil itself. To ascertain the pressure with the greatest degree of accuracy, samples should be taken with a specially designed sampler *vis-à-vis* the producing sands.

As production declines with the pressure drop in the natural reservoir, gas in solution will be less and viscosity of the oil increased. The presence of paraffin will be felt in its effect on the resistance offered to the flow and the increased propensity of the oil to plug.

Possible Causes of Failure—Liners.

(1) Shearing action of rocks due to their movement in a more or less lateral direction. Once this movement has started, there is small chance of any type or size of liner resisting such pressure.

(2) Movement of sand or shale may assume large dimensions, resulting in bending and possible collapse of the liner.

(3) Clays situated immediately above or between sands present a frequent source of danger to liners, especially if the dip of the strata is fairly steep. As the pressure is released, caves commence to form. No matter how small such caves may be, the clay will show a tendency to "creep," and, in doing so, will exert a lateral pressure on the pipe, causing it to bend. It will depend upon the manner in which this pipe is held directly above and below the portion affected whether this bending will develop into a kink and eventual collapse, or it may even result in complete rupture of the pipe.

(4) In the author's opinion, the presence of bodies of clay located immediately above and between producing sands is far more dangerous as regards liner failures than either sand or shale would be. Once a clay starts movement by "squeezing," no pipe manufactured will be able to withstand the pressure it will exert, and the steeper the dip, the more pronounced the pressure will become.

(5) As the pressure differential is comparatively low, the possibility of collapse being due to oil and gas pressure can be dismissed.

Sometimes other complications occur such as clay bands or soft shales interbedded with the sand. In the presence of water, no matter how small the quantity, these will tend to become plastic and "squeeze." Where the "breaks" are well defined and wide apart it is advisable to face them with blank pipe, but where the "breaks" happen to be in thin streaks little can be done. The best remedy in such a case is to keep the annular space between the wall of the hole and the pipe as small as practicable so as to offer the greatest resistance to the "creeping" clay or softened shale which will ultimately effectively plug the perforations.

It is well to remember that in addition to the inflowing oil and gas having the maximum number of points of ingress, the flow from the sand to the inside of the casing should always be by the straightest possible route.

Lateral or vertical movement of the oil and gas in the annular space between the producing sand and the pipe will result in wall attrition and induce caving in course of time.

Vibration.

Vibration plays a very important rôle in the effectiveness of screen pipe. Anyone who has had field experience can call to mind instances of flowing wells where the oil strings and tubing heads have been vibrating. Wherever this condition is apparent at the surface where everything is anchored down and therefore more or less rigid, one can be quite certain that a similar condition exists down the hole, and that the magnitude of the vibration of the oil string or liner may be probably greater *vis-à-vis* the sand, than is apparent at the surface. Since we know that when a screen is vibrated it will pass matter much more readily, one can picture what is taking place at the bottom of the hole when the screen pipe is vibrating, no matter how slight such vibration may be. The detrimental effects from vibration will be enhanced where the sand is soft and crumbly.

One of the disadvantages of free hanging oil strings is their inclination to excessive vibration. It still occurs in the case of hung liners, but to a lesser degree than where the liner is anchored to the previous column which has been cemented.

Where liners are stood on end the extent of vibration will depend how well the liner is supported and to what extent it may be either bent or kinked.

A cemented combination oil and water string is more or less rigid, and even under adverse flowing conditions will vibrate far less than any other type.

By controlling the gas and oil flow, vibration can be reduced to a point that it becomes practically non-existant at the surface, but in the majority of cases, especially where the " flow " is large, or, if not large, is irregular, a certain amount of vibration will exist. Even a slight vibration will lower the efficiency of the screen.

Joints.—Four types of joints are in general use in connection with oil-field practice. These are :—

1. Flush joint.
2. Square thread flush joint.
3. Swelled inserted joint.
4. Swelled and cressed semi-flush inserted joint.

Both these last types of joint are suitable for oil strings. As regard " pull-out " strength they equal collared pipe.

Setting of Liners—Condition of Hole.

The flush joint is the ideal type for liners or even for that section of the oil column which enters the gas/oil producing sand. Tight spots can be passed easily, and it is not so readily " hung up." This type of joint facilitates washing out of wells prior to their being brought into production as there are no collars to cause obstruction.

Casing with flush joints is freed with less difficulty than with other types of joint and washing over is simplified.

A further advantage is that the hole does not require to be reamed out to the same extent as would be necessary when using collared pipe. This is important, for little is to be gained by setting a liner, the primary function of which is to prevent caving and wall attrition, in a hole which is from 1 in. to 3 in. or more larger in diameter than the liner itself.

Although a liner should run in easily, it should not be a loose fit. For a liner to be really effective, especially where soft sands, loose shales or clays are present, the annular space between the liner and borehole should be kept as small as possible. This will minimise excessive movement of sand and hold thin layers of clay or shale in position.

Short liners are not difficult to set. The problem becomes more serious when liners several hundred to a thousand feet or more in length have to be set. Short liners up to 100 to 200 ft. in length may be stood on end and support their own weight, providing the hole is in first class condition—*i.e.*, not oversized, kinked or crooked and is free from caves. It is imperative that such liners be supported throughout their entire length and should stand as vertical as possible.

The common practice of standing long liners from 250–1000 ft, and more in length is surely not commendable, and is no doubt responsible for many subsequent troubles experienced. It requires only a little imagination to picture what the results will be of standing several hundred feet of comparatively light pipe on end in the form of a column, in a hole which is from one to three inches and more larger in diameter than the pipe's greatest circumference, irrespective of caves large and small.

As this column of pipe standing on end cannot support its own weight, it is bound to sag and will find support first on one side of the borehole, then on the other ; what is worse still, it will naturally conform to all irregularities of the borehole such as caves, etc. The pipe will become distorted and kinked, and will

suffer most just close to the joints. Should the pipe follow into a cave of even small dimension, it may result in so acute a kink as to partly or wholly fracture the pipe at the threading by the joint.

Bent or kinked liners, or liners of smaller diameter than the size of hole will result in :—

(*a*) Reduced effective diameter.

(*b*) Free passage of tools hindered if not entirely precluded.

(*c*) Difficulty in pulling liners.

(*d*) Will start caving.

It is not an uncommon occurrence to hear the remark after a liner has parted : " We only took a light pull and the liner parted." It is quite correct that only a light pull was taken which would never have parted the pipe had it been in good condition. The fact remains that the pipe was already fractured through bending and kinking, so it only needed a " slight pull " to sever it.

Where the open space between the pipe and the borehole may be as much as $\frac{1}{2}$ in. to 3 in., and more in certain sections, caving will result. It is quite a simple matter to start caving but a difficult matter to arrest, for once begun the evil becomes aggravated and effects cumulative. As caving progresses, the liner will conform more and more to the contours of the hole, thus adding to the difficulties of an already troublesome situation.

If the condition of the hole is satisfactory, liners over 150–200 ft. should be hung from the inside of the previous string of casing. By hanging vertically the pipe will be in tension as it was designed to be, and not in compression as when standing on end.

The chief function of many liners is to act as a screen to hold in position loose sand and silts. Nevertheless, precaution is not always taken to seal off the annular space between the top of the liner and the preceding column. Through this neglect the effectiveness of the screen is nullified from the outset because a portion of the oil and gas will flow vertically up the annular space between the liner and the wall of the borehole, carrying with it sand and other detritus which the screen was designed to hold in check. This detritus will be deposited gradually inside the liner, slowly but surely silting it up.

Condition of Flow and its Effect on Liners.

The flow of gas and oil from a well where perforated or screen pipe is used to restrain movement of the sand must be maintained at an even a rate as possible, so as to avoid disturbing the natural filter formed by the coarser grains of sand banking up against the screen openings, thereby holding the smaller grains in check.

Where a well-proportioned screen is used some sand will be produced during the initial stages of a well being brought into production ; this will get less and less as the sand filter builds itself up behind the screen openings.

Production of sand with the oil usually ceases within the first 48 hours, and is sure proof that the natural filters have been formed. Care should be taken to allow this favourable state to remain undisturbed by avoiding changing of the characteristics of the "flow." A sudden change may result in the destruction of the naturally formed sand filters.

Altered conditions of flow may arise from mechanical adjustments at the surface or a change in the rate of flow from the sands, as also from bad conditions of flow up the well, causing gas heading and slippage.

Once a well has settled down, sudden changes, such as shutting down the well completely, or rapid changes of bean or choke sizes either up or down should be avoided. If necessary to adjust the "choke," the process should be as gradual as possible ; changing down is not quite as harmful as beaning up.

Whereas abrupt changes in the rate of flow from the sand itself are fairly exceptional, changes in the flow characteristics up the well are of common occurrence and generally attributable to unsuitable size of flow tubing, or, in some cases to an imperfectly designed "choke," which causes the flow to pulsate or become erratic. As a result the pressure differential at the bottom of the well will show considerable variation instead of remaining as constant as possible for optimum conditions.

Sudden pressure differential variations are very harmful to sand conditions. They will start the sand flowing through the screen, and if the pulsations are of fair magnitude one can assume the oil and gas to be flowing "in gusts" from the sand to the well. This type of flow will cause sloughing of the hole.

Initial Production Rates.

When handling a well during the initial stages of production, the flow should be carefully regulated.

Where a well is allowed to blow more or less "free" whilst it is being brought in, even if only for a short period, sand will be produced and carried through the screen at high velocity and this will inevitably damage the screen.

Lack of technique is shown in the harmful practice of only partially washing a well clean with water, then relying on the force and volume of its production to clear it of drilling mud which can only be accomplished if the well is permitted to flow violently.

The sudden release of pressure will tend to break down the sand and the high velocity at which the gas/oil/sand mixture

passes through the screen openings cause such abrasion as to partially, if not totally, destroy the screen's efficiency. As a consequence, the optimum production will have to be curtailed by " beaning back," thereby applying excessive back pressure in the effort to control sand production. This not only reduces the rate of flow, but through " beaning back " the velocity of the column of gas/oil/sand mixture will be decreased, sand will settle out almost immediately and the sanding up of the liner from the inside commences.

Some operators express the opinion that the production of sand is beneficial to a well as it loosens the " pay-sand " and opens up the channels. Others take the opposite view and believe the harmful effects arising from allowing the well to blow free and make sand more than counterbalance any good which might otherwise accrue.

It does not seem logical to disturb and produce sand which is so loosely cemented that it is easily disintegrated and can be produced with the oil. Surely this is sufficient proof that the sand is open and (for its particular type) offers minimum resistance to movement of oil and gas.

By producing sand, cavities will be created ; these will tend to undermine the overlaying rocks or interbedded shale or clay beds. After these have been so undermined they are bound to cave in sooner or later, and will result in plugged perforations, crushed or lost liners.

Damaged water shut-offs may be traced to movement, or partial or total collapse of the overlaying beds caused by the oil sands caving away. This applies especially where the water shut-off has been effected immediately above the oil producing zone. It is always advisable to disturb the sand as little as possible, where it is not well cemented together.

One often hears the remark that a well is only making 1 per cent. of sand. If this is converted into cubic feet it may be anything from 50 to 200 cu. ft. or more per 24 hrs., yet operators seem astonished that a well so producing should behave in an erratic manner and show a sharp decline curve.

Rate of Flow Through Sand to Well.

A big drop in the pressure differential across the sand adjacent to the hole is an indication that free gas, in addition to that coming out of the oil, is expanding rapidly and passing through the sand with increasing velocity. Its maximum velocity and disruptive power will be at the wall of the borehole causing the sand to disintegrate. Therefore, if the producing sand is loose and inclined

to crumble, it would seem advisable to produce the sand and oil under greatest possible back pressure.

The Effect on Production Using an Efficient Versus Inefficient Screen.

Where a screen allows sand to pass, the only means for alleviating this evil is to " bean " the well back, thereby increasing the back pressure. This will, however, curtail the production per unit of time, whereas if a screen allows bridging by the larger grains of sand on the outer surface, the maximum production that will pass the screen openings at such a velocity as will not disturb the natural sand filter, can be taken.

It has been proven that the behaviour of a number of wells drilled into the same pay-sand under identical conditions with regard to depth, pressure, size of liners and flow tubing, but with different sized perforations, slots or screen openings, has differed considerably. Some of the wells had to be " beaned " back to hold sand in check, and in consequence of the increased back pressure they produced in some cases but a third of the quantity of oil yielded by others equipped with better proportioned screens.

Plugging of Screen Pipe—Back-Washing.

Unfavourable sand conditions, as for instance sand which contains a large percentage of flour-like fine particles of clay, are very liable to cause plugging of the screen after the well has been producing for some time. This difficulty can be effectively overcome by " back-washing," using either oil or oil and gas. Production will generally increase after a liner has been properly "back-washed," due to the unplugging of the apertures which affects and lowers the pressure differential across the screen.

A well will be prone to make a certain amount of sand following "back-washing." If production is taken easily and not forced, a new natural sand filter will be gradually built up.

Light crude or a prepared crude containing casing-head gasoline should be employed for "back-washing." When the trouble is due to plugging of the screen by paraffin, it may be doctored in addition with any of the reputable dissolvent compounds on the market, and used together with casing-head gas for " back-washing."

Washing a Well Clean of Mud.

The necessity for washing the lower part of a well clean from rotary mud is generally recognised, but when screen pipe or, in fact, any type of liner is used, it becomes imperative.

Extraordinary results of tests carried out by A. E. Carr give definite proof that straight rotary mud will completely clog and render screen pipe ineffective.

A brief description of these tests is as follows :—

To Circulate a Normal Rotary Mud at the rate of 1100 barrels per day of 24 hours required :

Weight of mud per cu. ft.	Pressure required.
67·5 lb.	200 lb. per sq. in.
71·3 lb.	300 lb. per sq. in.
73·1 lb.	Completely clogged the screen.

When 2·200 lb. pressure per sq. in. was applied, it was still impossible to pass additional mud.

The above tests show how necessary it is that rotary mud should be reconditioned and reduced to the lowest possible viscosity before any kind of screen pipe is run, and illustrates how very vital is the importance of washing the annular space between the wall of the hole and the screen or liner free of mud, more especially so where " Barytes " weighted mud is used.

" Barytes " laden mud has undoubtedly a higher clogging effect than ordinary rotary mud, and will constitute a real danger if left *in situ* behind a liner. When it contains a fair percentage of sand or shale, it soon becomes plastic and develops into an almost solid mass in course of time. In such condition it forms an ideal plastic cement.

Nowadays the majority of wells are brought into production through a column of tubing, which, if set at a proper depth, minimises if it does not entirely eliminate the chance of mud being left in the hole.

Providing the tubing shoe is run as close to the bottom as practicable, it will assure the upward flow starting from near the bottom of the well and will greatly assist to keep the well free of mud and other sediment.

If a properly designed tubing column is used and excessive back pressure not applied, the velocity of flow (minimum rate to be not less than 6–8 ft. per sec.) will enable the well to free itself of practically all mud and other sediment which the well may be making, before it has time to settle out. The practice of setting the shoe of the tubing 100–500 ft. or more up the hole is not taking the best advantage of this method of flow.

Where several sands have to be developed simultaneously it is obvious that the tubing shoe should be set as near to the bottom of the well as possible, especially if there is a big increase of depth as measured from the upper sand to the lower sand. In some cases this may amount to several hundred feet. In order to illustrate this point the following example will apply :—

Total Depth of Well—3685 Ft.

1st Sand.		2nd Sand.		3rd Sand.		4th Sand.	
Depth.	Thickness.	Depth.	Thickness.	Depth.	Thickness.	Depth.	Thickness.
Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
3035	45	3230	23	3490	18	3610	75

Depth of shoe of last casing column, 3025 ft.
Length of liner, 680 ft.
Maximum rock pressure, 1750 lb. per sq. in.
Tubing shoe set at 3200 ft. (therefore length of hole untubed 485 ft.).

Assuming the ascending column of oil and gas to have a specific gravity of 0·6 and the well flowing against a tubing head back pressure of 580 lb. per sq. in., the tubing shoe pressure will be approximately 1414 lb. per sq. in.

The back pressure on the 3rd sand will be 1484 lb. per sq. in. plus screen friction.

The back pressure on the 4th sand will be 1520 lb. per sq. in. plus screen friction.

Under these optimum conditions, assuming that the well is washed absolutely clean of drilling mud, the 3rd and 4th sands will have a fair chance of coming into production because the difference between the total back pressure on the 4th sand and the rock pressure will be approximately 230 lb. per sq. in.

Compare these conditions with those which would apply if weighted mud is left in the hole when the well is first brought into production, assuming the weight of mud used for drilling to be 112 lb. per cu. ft., specific gravity 1·8, with the tubing shoe at the same depth.

As washing operations progress, that column of mud above the depth at which the tubing shoe is set, viz., 3200 ft., will become progressively lightened. After the weight has been sufficiently reduced, the 1st and 2nd sands will commence to become active. As the column of mud and oil above these two sands becomes increasingly lighter, the production from these sands will increase until finally practically clean oil will be produced. It is at this point that the well will be turned through the primary bean and back pressure applied. Assuming the sp. gr. of the oil flowing from the well (which is slightly contaminated with mud) to be 0·700, with a tubing head back pressure of 580 lb. per sq. in., the back pressure on the 1st and 2nd sands will be approximately 1561 lb. per sq. in.

The 3rd and 4th sands, however, situated at 3490 ft. and 3610 ft. respectively, or, 237 and 357 ft. respectively below the 2nd sand will still be covered by mud, and unless the well is permitted to flow in a more or less "wild" state for some little time there is no chance whatever of the mud being ejected. There will be a column of mud-laden fluid between the 2nd and 3rd sand measuring 237 ft., the sp. gr. of which will not be less than 1·5. The total back pressure on this sand will be 1717 lb. per sq. in. plus screen or liner friction. The condition of the 4th sand will be still worse,

as the column of mud below the 3rd sand will be in its original condition as regards weight, therefore having a specific gravity of 1·8 or more. As the difference between the bottom of the 3rd sand and the top of the 4th sand is 102 ft., the total approximate back pressure on this sand will be 1797 lb. per sq. in. plus screen or liner friction, which may easily approximate 50 to 100 lb. per sq. in., depending on size of liner and viscosity of the mud.

Had the tubing shoe been set at 3590 ft., and the well thoroughly washed under control, the moment the fluid column had become sufficiently lightened the 4th sand would have commenced to produce and have rid the well of all mud below the tubing shoe. In other words, all four sands would have become active at practically the same time.

In making these calculations frictional losses have not been taken into consideration.

Heat Transfer for Fluids in Turbulent Flow in Pipes.*

By R. CHANDLER (Student).

THE problem of predicting the heat transfer coefficient between a pipe and a fluid flowing inside in turbulent motion has been attempted in many ways. Equations have been developed from time to time purporting to apply to the case, and such equations, when used within the range of variables supported by experimental data, are often quite reliable, but the majority of them contain more factors than have been experimentally investigated.

THE CONDITIONS EXISTING IN A FLUID IN TURBULENT FLOW IN A PIPE.

In turbulent flow the velocity parallel to the axis varies radially, being greatest at the axis of the pipe. The velocity distribution in air flowing turbulently in a pipe has been determined by Stanton,[1] using a Pitot tube small enough not to disturb the flow.

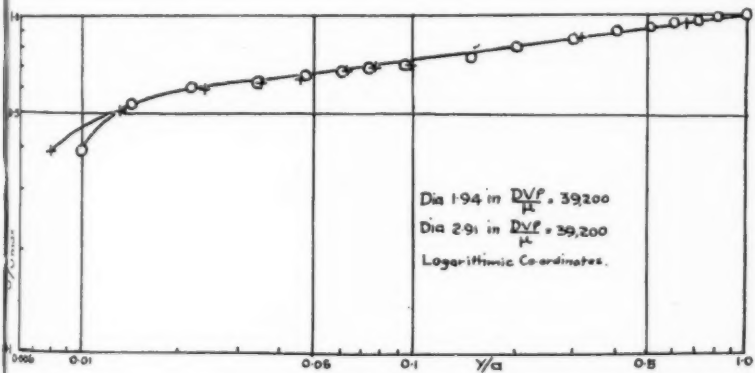

Fig. 1.

Fig. 1 is based on the data of Stanton for air flowing isothermally through two tubes of different diameters, but for the same value of the Reynolds number. The ratio of the velocity (u) at a point to the maximum velocity (u max.) is plotted against the ratio of the radial distance (y) of the point from the wall to the radius (a) of the pipe, and agreement between the two sizes of tube is good.

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* Paper awarded Students' Medal and Prize, 1932–1933.

[1] Stanton, *Proc. Roy. Soc.*, 1911, **A85**, 366.

With different values of maximum velocity, Stanton found similar velocity distribution from the axis up to the point y/a=0·2, and beyond this the curves were separate. Later, Stanton, Marshall and Bryant[2] made velocity explorations nearer to the tube wall by means of a modified Pitot tube, which was calibrated by taking measurements with the air in laminar flow, for which the velocity distribution could be calculated, since it followed a simple parabolic law. The curves of velocity distribution obtained for turbulent flow showed that the eddies began to decrease at a certain distance from the wall, as the wall was approached, and that, very near the wall, the fluid was in apparent laminar motion.

A zero velocity at the wall itself was indicated. The distribution of velocity in air flowing isothermally parallel to a plate has been determined,[3] and some results, plotted with logarithmic co-ordinates

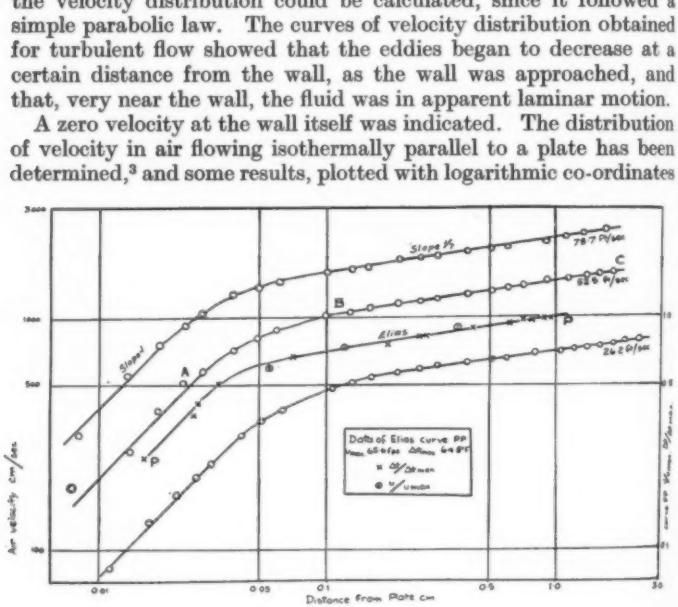


Fig. 2.

in Fig. 2, appear to show the existence of a layer in laminar motion adjacent to the surface of the plate, by a line of unit slope (OA). From A to B the slope decreases, indicating that eddies, which first become apparent at A, increase from A to B. For the main body of the air the eddies are constant, and the slope of the line BC is $\frac{1}{7}$. With increased velocity the thickness of the laminar layer is decreased. The results are similar to those obtained by Stanton for pipes.

[2] Stanton, Marshall and Bryant, *Proc. Roy. Soc.*, 1920, A**97**, 413.

[3] Data of Van der Hegge Zijnen given by McAdams, "Heat Transmission," McGraw-Hill, 1933.

With roughened pipes velocity measurements, plotted as $\log \frac{u}{u \text{ max.}}$ against $\log \frac{y}{a}$, give a straight line for the main body of the air, as in the case of smooth pipes, but the slope of the line is greater.[1] Similar results have been obtained for air flowing parallel to a rough plate,[3] and the slope of the line representing velocity distribution in the turbulent zone is greater than in the case of a smooth plate. These velocity explorations appear to indicate : (A) that there is a layer in laminar motion adjacent to the pipe wall, with a velocity of zero at the wall itself ; (B) that between the laminar layer and the turbulent core the motion is characterised by eddies increasing from zero to their constant value for the core.

However, Fage and Townend[4] have found, by ultramicroscopic observations of water in turbulent flow in pipes, that the motion is not perfectly laminar near the boundary. A microscope of

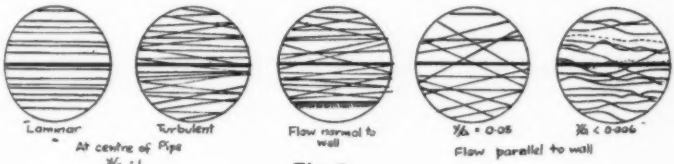


Fig. 3.

magnification 200 was focused on the surface of a pipe, and particles within a distance of 0·001 in. from the surface were in focus. The view obtained, sketched in Fig. 3, showed a large number of particles moving in sinuous paths and a few very slow moving particles. The distance of the slowest particles from the surface of the pipe was predicted, from their velocity, to be 1/40,000 in. The particles usually crossed and recrossed the hair line in the microscope several times.

Fage and Townend state that " the impression formed was that no particle was ever seen about which it could be said with conviction that its motion was rectilinear."

When a finite amount of heat is being transmitted there is a temperature gradient in the fluid. Since the properties of a fluid which determine its flow vary with temperature, a modification of the velocity distribution for isothermal flow is to be expected. Pannell[5] made velocity and temperature explorations across an air stream flowing upwards in turbulent motion in an electrically

[4] Fage and Townend, *Proc. Roy. Soc.*, 1932, **A135**, 656.
[5] Pannell, Aero Research Comm., Rept. Memo., 243 (June, 1916).

heated vertical brass pipe. In Figs. 4 and 5 the results of a run, made with the pipe wall at a temperature of 109·4° F. and an air temperature at the axis of 75·9° F. are plotted. The distributions

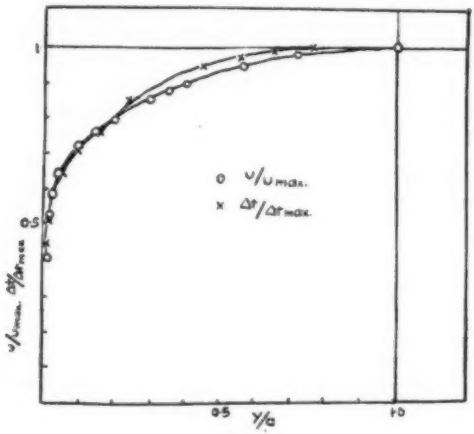


Fig. 4.

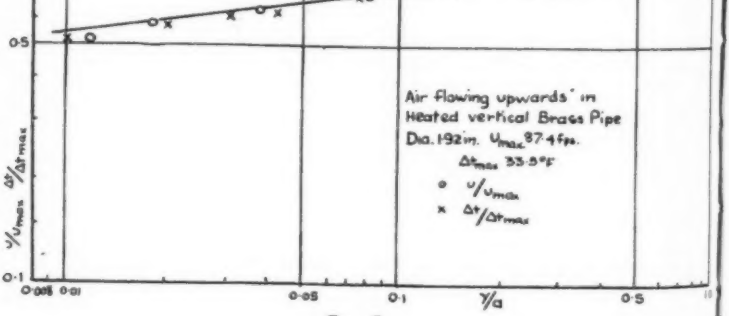


Fig. 5.

of temperature and air velocity are not the same for the whole section. The curves resemble the velocity distribution curve for

isothermal air flow in a pipe, and, when plotted to logarithmic co-ordinates, give the same slope.

For air flow parallel to a heated plate velocity and temperature distributions (Fig. 2) are very nearly the same, and resemble the velocity distribution for isothermal air flow parallel to a plate.[6]

In the comparatively small range between the temperature of the wall and the temperature of the air in Pannell's experiments, the variation in the viscosity is very small, and this would account for the resemblance of the velocity curve to that for isothermal air flow.

Comparing the vector equation of motion of a fluid with the equation for heat transmission, where c is the specific heat at constant pressure, k the thermal conductivity and μ the absolute viscosity, for similarity of temperature and velocity distribution $c\mu$ must be equal to k, and, corresponding to those points in the fluid where pressure gradients exist, we must have sources of internal heat. In pipe flow, heat is supplied or extracted at the wall only, while an axial pressure gradient exists at every point of the fluid. Consequently, correspondence of temperature and velocity cannot be expected. Regarding the condition that $\frac{c\mu}{k}=1$, this expresses the fact that in the fluid in which similarity may be expected, momentum and heat conduction are caused by diffusion of the molecules.

For air $\frac{c\mu}{k}=0{\cdot}73\doteqdot 1$, while for water at 20° C. $\frac{c\mu}{k}=7{\cdot}1$. Hence for liquids there can be no similarity, while for gases, only those parts of the fluid where no pressure gradients exist will show similar distribution of temperature and velocity. Explorations across a stream of water in turbulent motion in a heated pipe show that the velocity and temperature distributions are not the same, and that they vary with the value of the Reynolds number.

Thus in Fig. 6, plotting $\frac{u}{u\ max.}$ against y/a to logarithmic co-ordinates for the upper portion of the pipe, runs at $\frac{DV\rho}{\mu}$ =40,700 and 80,400 gave slopes of 0·29 and 0·15 respectively, as compared to 0·06 and 0·06 for the slopes of the temperature distribution curves in similar runs. With low velocities free convection was found to distort the curve of temperature distribution, and even at a velocity of 8 ft./sec., the curve was not symmetrical.

[6] Data of Elias given by McAdams.[20]

Theory of Heat Transfer in Turbulent Flow.

Osborne Reynolds[8] advanced a theory for heat transmission in a fluid by drawing an analogy between the mechanisms of fluid friction and heat transfer. His theory, as outlined by Stanton,

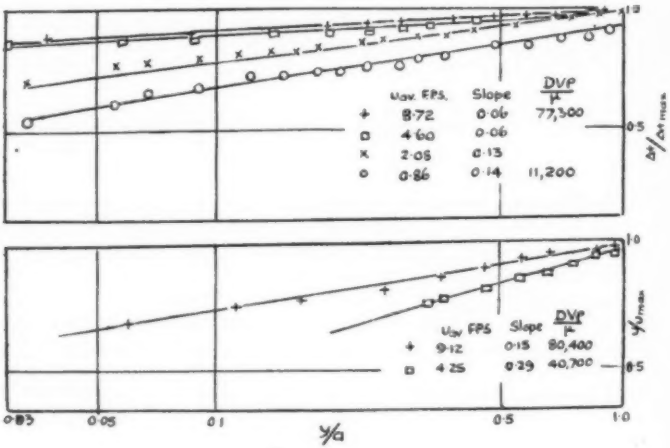


Fig. 6.

follows. The transfer of heat between a fluid and a solid in contact, for a given difference of temperature between them, will be proportional to the rate at which fluid particles are carried up to the surface, in other words, to the diffusion of the fluid in the neighbourhood of the surface. This may be the diffusion of molecules in a mass at rest, or by means of the movement of small portions of the fluid in the form of eddies.

The transmission of heat by molecular diffusion constitutes what is known as the thermal conductivity of the fluid. In the case of laminar motion, the transfer of momentum between adjacent layers, which constitutes the phenomenon of viscosity, is effected by the molecular diffusion of the fluid, and, in the case of turbulent motion, the corresponding phenomenon of mechanical or eddy viscosity is due to the mass diffusion brought about by the eddying motion. It seems, therefore, that the transfer of momentum, which constitutes frictional resistance, and the transfer of heat are brought about by the same mechanism in both laminar and

[8] Reynolds, *Proc. Man. Lit. Phil. Soc.*, 1874, 8.

turbulent flow. Stanton[9] derived an equation, by applying Reynolds' theory, for the case of heat transfer between a pipe and a fluid flowing in turbulent motion through it, neglecting the boundary layer. The ratio of the momentum lost by skin friction between any two sections, distant dx apart, to the total momentum of the fluid will be equal to the ratio of the heat transferred to the heat which would have been transferred if the whole of the fluid had been carried up to the surface of the pipe and attained the temperature of the pipe :—

$$\frac{dp\pi D^2}{\frac{4W}{g}V} = \frac{dt}{T_w - T_m}$$

D=diameter of the pipe.
V=mean velocity of flow.
W=weight of fluid passing per second.
T_w=temperature of the wall of the pipe.
T_m=mean temperature of the fluid.
dp=fall in pressure between the sections.
dT=rise in temperature of the fluid between the sections.

Skin-friction per unit area of the pipe is given by :—

$$R = \frac{\pi D^2 dp}{4\pi D dx}$$

Q, the heat transmitted per unit area of the pipe is

$$\frac{c\,\frac{W}{g}\,dT}{\pi D dx.}$$

Where c=Specific heat of the fluid at constant pressure.

Hence $$Q = \frac{Rc\ (T_w - T_m)}{V}$$

The heat transferred per unit area of the pipe per °F. difference in temperature between the fluid and the pipe is given by :—

$$h = \frac{Rc}{V}$$

A general law of resistance for pipes of all dimensions and for all rates of flow was obtained by Reynolds. He found that $\frac{R}{R_c} = \frac{V}{V_c}$ Where R_c and R are the frictional resistances per unit area of pipe surface at the critical velocity V_c, and at a velocity V, above it. Since V_c was found to be given by $\frac{V_c D\rho}{\mu} = B$, where B is a dimensionless constant and μ is the viscosity of the fluid, and

[9] Stanton, *Phil. Trans. Roy. Soc.*, 1897, **A190**, 67.

R_c, from the streamline theory, is known to be equal to $\frac{4V_c\mu}{D}$, we have by substitution :—

$$\frac{R\rho D^2}{4\mu^2 B} = \left(\frac{DV\rho}{B\mu}\right)^n$$

Hence

$$R = 4\ V^2\rho \left(\frac{DV\rho}{\mu}\right)^{n-2} \frac{1}{B^{n-1}}$$

$$= fV^2\rho$$

Where f is a function of $\frac{DV\rho}{\mu}$ which depends on the nature of the surface of the pipe.

Therefore the coefficient of heat transfer, h, is given by

$$h = fcV\rho$$

or,

$$\frac{hD}{k} = f\left(\frac{DV\rho}{\mu}\right)\left(\frac{c\mu}{k}\right)$$

k=coefficient of thermal conductivity of the fluid. The lower line in Fig. 7 represents this equation when f is given values determined for isothermal flow in smooth pipes, and $\frac{c\mu}{k}$ is given its average value of 0·73, since the value of this group varies very slightly for gases.

It has been shown that the same turbulent conditions do not exist up to the pipe wall, hence the equation can only be expected to be correct in the case of a fluid in which the processes of molecular and molar movement are similar, since in the derivation it was assumed either that the same turbulent conditions existed up to the surface of the pipe, or that molecular and molar diffusion in the fluid were similar. In gases, the rapid to and fro movement of the molecules, which leads to the properties of viscosity, and heat conduction, is very similar to the molar diffusion of particles in a turbulent fluid, and the Reynolds equation should hold.

In liquids, transmission of heat and momentum takes place mainly, not by the diffusion of the molecules, but by transfer from one molecule to the next, due to their proximity. There is, then, no similarity between the molecular and molar transmissions of heat and momentum in the case of liquids. The Reynolds equation is in fairly good agreement with experimental data for gases, but does not hold in the case of liquids.

Prandtl-Taylor Equation.—Prandtl[10] and later Taylor[11] derived an equation for heat transfer in which part of the resistance to heat flow was assumed to be in the turbulent core, and the rest in a layer flowing in laminar motion adjacent to the wall of the pipe.

[10] Prandtl, *Physik Z.*, 1910, **11**, 1072.
[11] Taylor, Advisory Comm. Aero., Tech. Rept., 1916–17, **2**, 423.

If v is the velocity of the surface between the boundary layer, assumed to be in laminar motion, and the turbulent core, the thermal resistance of the core is

$$\frac{V-v}{Rc}$$

If b is the thickness of the laminar layer, the thermal resistance of this layer is $\frac{b}{k}$

We have $R = \mu \frac{v}{b}$ or $b = \frac{v\mu}{R}$

The total thermal resistance is given by

$$\frac{1}{h} = \frac{V-v}{Rc} + \frac{v\mu}{Rk}$$

The coefficient of heat transfer is given by

$$h = \frac{Rc}{V\left(1-m+m\frac{c\mu}{k}\right)} \text{ where } m = \frac{v}{V}$$

Since $R = fV^2\rho$

$$h = \frac{fcV\rho}{1-m+m\frac{c\mu}{k}}$$

or

$$\frac{hD}{k} = \frac{f\left(\frac{DV\rho}{\mu}\right)\left(\frac{c\mu}{k}\right)}{1-m+m\frac{c\mu}{k}}$$

Various values for m have been obtained from experimental data, Sherwood and Petrie[12] found :—

	Range of m.	Average m.
Water	0·22–0·90 ..	0·595
Acetone	0·25–0·71 ..	0·48
Benzene	0·12–0·80 ..	0·43
Kerosine	0·10–0·62 ..	0·31
n-Butyl alcohol	0·32–0·62 ..	0·38

Assuming both the temperature and velocity in the turbulent core to vary directly as the one-seventh power of the distance from the pipe wall, and assuming undisturbed laminar motion in the boundary layer, Prandtl[13] using an empirical equation for the friction coefficient f, obtained the relation :—

$$m = 1{\cdot}75\left(\frac{DV\rho}{\mu}\right)^{-\frac{1}{8}}$$

[12] Sherwood and Petrie, *Ind. Eng. Chem.*, 1932, **24**, 736.
[13] Prandtl, *Physik Z.*, 1928, **29**, 487.

However, Prandtl stated that the data require that the value for the proportionality constant should range from 1·1 to 1·2, instead of being 1·75. He attributes the discrepancy to the lack of a sharp boundary between the turbulent core and the assumed laminar layer. Woolfenden's curves of velocity and temperature distribution in water being heated in turbulent flow in pipes show that Prandtl's assumptions of similar temperature and velocity distribution are not valid in the case of water. Prandtl recognised that temperature and velocity distribution can only be the same when $\frac{c\mu}{k} = 1$.

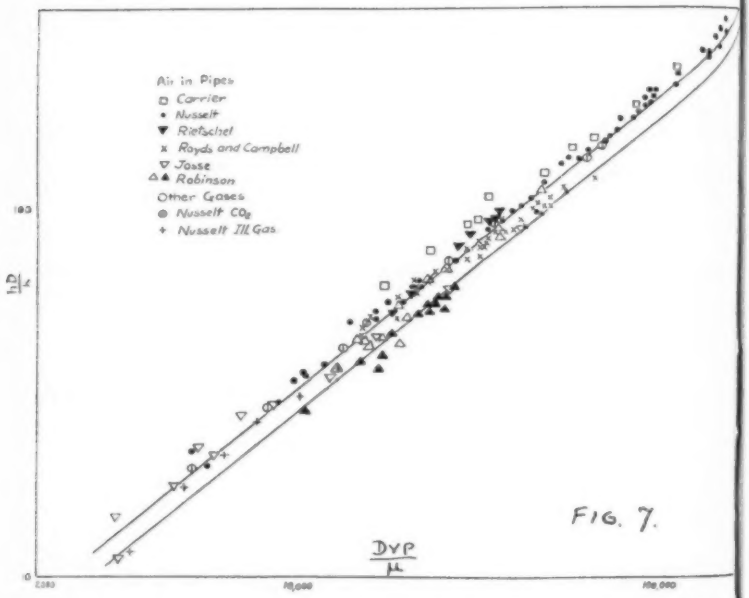


FIG. 7.

For gases the Prandtl-Taylor equation is in good agreement with the experimental data available. The upper line in Fig. 7 represents the equation, substituting $\frac{c\mu}{k} = 0{\cdot}73$ and $m = 0{\cdot}3$. For gases the required condition, that $\frac{c\mu}{k} = 1$, is approximately true.

Other Equations.—Eagle and Ferguson[14] consider a layer of fluid

[14] Eagle and Ferguson, *Proc. Roy. Soc.*, 1930, **A127**, 540.

between an assumed laminar layer and the turbulent core, in which the eddies increase from zero to their constant value for the turbulent core. The thermal resistance of the core in the Prandtl-Taylor equation is $\frac{1-m}{f V\rho c}$: it is independent of $\frac{c\mu}{k}$. The thermal resistance of the laminar layer is $\frac{m}{f V\rho c}\ \frac{(c\mu)}{k}$: for a given value for the Reynolds number, the thermal resistance varies directly as $\frac{c\mu}{k}$. It is deduced that the thermal resistance of the intermediate layer, for a given value of the Reynolds number, must vary as $\left(\frac{c\mu}{k}\right)^n$ where $O<n<1$. Then $\frac{V\rho c}{h}$ must behave like an expression of the form :—

$$X + Y\left(\frac{c\mu}{k}\right)^n + Z\left(\frac{c\mu}{k}\right).$$

The data of Eagle and Ferguson are not correlated better by their method than by the Prandtl-Taylor equation.

Caldwell[15] derives a relation between the " coefficient of heat conductivity in turbulent flow " and the coefficient of mechanical viscosity.

The coefficient of heat conductivity in turbulent flow, k^1, at a point, may be defined as the heat transmitted per unit area per second for unit temperature gradient at this point. The coefficient of mechanical viscosity, μ^1, at a point in a fluid in turbulent motion, is defined as the momentum transmitted per unit area per second for unit velocity gradient at this point, $= \frac{F}{\frac{du}{dy}}$ where F is the shearing stress and $\frac{du}{dy}$ is the velocity gradient. It was assumed that, since molecular speeds are high, the molecular conduction of heat and momentum acted independently of the molar processes. The heat transmitted per sec. per unit area for unit temperature gradient due to the molar diffusion alone was (k^1-k). Similarly, the diffusion of momentum due to turbulence was $(\mu^1-\mu)$. Considering a plane in the fluid.

$$\frac{\text{Momentum diffused in a given time}}{\text{Heat diffused in the same time}} = \frac{m}{h} = \frac{1}{c}.$$

Where m and h are the mass and heat capacity of each particle passing through the plane, and c is the specific heat per unit mass.

Hence $$\frac{k^1-k}{\mu^1-\mu} = c.$$

[15] Caldwell, *J. Roy. Tech. Coll.*, Glasgow, 1931, **2**, 409.

The determination of molar viscosity in a given case of turbulent flow requires a knowledge of the velocity distribution. As the manner of the variation of velocity distribution with varying Reynolds number is not clear, no general expression for μ^1 can be given. Murphree[16] assumed the flow in the boundary layer not to be laminar, but to be such that the eddies increase continually from zero at the pipe wall to a value which is constant for the main body of the fluid. Where E is the constant value of eddy viscosity over the main body of the fluid, μ^1 at a point in the "film" was assumed to be given by

$$\mu^1 = E\left(\frac{a-r}{a-b}\right)^3$$

Where r is the distance of the point from the axis of the pipe, a the radius of the pipe, and b the inside radius of the film. The heat transfer coefficient derived is a complicated function of $\frac{DV\rho}{\mu}$ and $\frac{c\mu}{k}$. Values of the friction factor, f, for isothermal flow have to be used, and the temperature at which the properties of the fluid have to be taken was chosen arbitrarily to obtain the best correlation of experimental data.

The Principle of Dimensional Similarity.

The principle of dimensional similarity provides a method of correlating data, by means of which their range of application may be greatly extended. The method depends on the property of all fundamental equations, that such equations are independent of the units involved; all the factors can be arranged into groups which are dimensionless. The experimental data available are not usually sufficiently complete for the determination of the effect of each individual variable, but gathering these variables into dimensionless groups reduces the problem to one of finding the group functions only. Wherever possible, however, correlations should be supported by data where each factor is varied in turn. The principle of similarity can only be applied to one shape of body at a time, and, if its surface is rough, it is necessary that the magnitude of the irregularities should be in proportion to the size of the body. In practice, it being impossible to distinguish between different surfaces in this way, the heat transfer can only be represented as being some fraction of the corresponding heat transfer for a smooth surface. The principle is of great value in planning experiments, and has been widely used for predicting the behaviour of full-scale equipment from experiments carried out on models. Similar systems require the same values for the dimen-

[16] Murphree, *Ind. Eng. Chem.*, 1932, **24**, 726.

sionless groups, and all the factors likely to be involved have to be known.

The fundamental dimensions involved in heat transfer problems, when there is no inter-conversion of heat and mechanical energy, are mass [M], length [L], time [T], temperature [θ], heat [H]. The factors assumed to be involved in the case of heat transfer between a pipe and a fluid flowing in turbulent motion through it are :—

D, the diameter of the pipe, [L] ;

V, linear velocity of flow of the fluid, [L] $[T]^{-1}$;

ρ, density of the fluid [M] $[L]^{-3}$;

c, specific heat of the fluid at constant pressure, [H] $[\theta]^{-1}$ $[M]^{-1}$;

μ, absolute viscosity of the fluid, [M] $[L]^{-1}[T]^{-1}$;

k, coefficient of thermal conductivity of the fluid, [H] $[T]^{-1}$ $[L]^{-1}$ $[\theta]^{-1}$;

h, coefficient of heat transfer, [H] $[L]^{-2}$ $[\theta]^{-1}$.

Natural convection and the change of the fluid properties with temperature are neglected. Since the properties of all fluids change with temperature, the coefficient of heat transfer being considered is actually the coefficient in the limit when the heat transfer approaches zero. These factors can be arranged in the dimensionless groups $\frac{hD}{k}$, $\frac{DV\rho}{\mu}$ $\frac{c\mu}{k}$, and simple power functions of these groups are used to correlate heat transfer data as[17] :—

$$\frac{hD}{k} = a\left(\frac{DV\rho}{\mu}\right)^{n}\left(\frac{c\mu}{k}\right)^{m}$$

the available data, while they do not prove that each factor is involved do indicate that most of them are.

The group $\frac{D}{L}$, where L is the length of the pipe, is sometimes used in the equation, and two different aspects of the possible effect of the tube length have been discussed by various writers. As the fluid flows along the tube, the layers near the wall become heated nearly to the temperature of the wall, and the rate of heat flow per degree temperature difference between fluid and wall would be expected to decrease. This effect, while important in the case of viscous flow, will not influence, except to a very slight extent, the heat transfer to fluids in turbulent flow, since the temperature gradient in the main body is almost negligible, and the main resistance to heat flow is in the relatively thin layer, at the boundary. The heat absorbed and given up by this thin layer is negligible in comparison with the heat absorbed by the main body.

[17] Nusselt, *Z. Ver. deut. Ing.*, 1909, **53**, 1750, 1808.

The second effect of tube length is due to the increased turbulence near the tube entrance making the boundary film thinner, and this would be expected to increase the rate of heat flow. Bends and contractions and other irregularities would have the same effect. Lawrence and Sherwood[18] carried out experiments on the heat transfer to water in turbulent flow in an apparatus designed so that end effects would be present, and found no appreciable effect on the heat transfer in the range, of the ratio of heated length to diameter, from 59 to 224. It would be necessary to carry out experiments with shorter pipes in order to determine end effects.

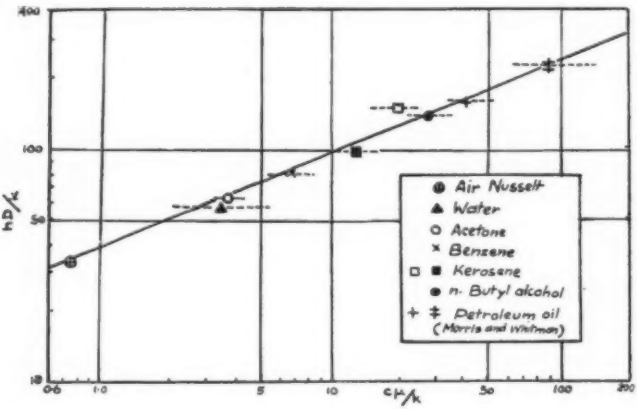


Fig. 8.

Sherwood and Petrie[12] plotted their own data for heating four different liquids, the data of Nusselt for air and of Morris and Whitman for several petroleum oils, with $\log \frac{hD}{k}$ as ordinates and $\log \frac{DV\rho}{\mu}$ as abscissæ. They obtained a line for each fluid having a slope of about 0·8. At $\frac{DV\rho}{\mu} = 10{,}000$, the value of $\frac{hD}{k}$ for each fluid was read from these lines, and $\log \frac{hD}{k}$ was now plotted against $\log \frac{c\mu}{k}$, using the fluid properties at main body average temperature.

In Fig. 8 the range of $\frac{c\mu}{k}$ for each fluid is indicated by a

[18] Lawrence and Sherwood, *Ind. Eng. Chem.*, 1931, **23**, 301.

horizontal dotted line. The slope of the line drawn through the points was found to be 0·4 ; the range of $\frac{c\mu}{k}$ covered was from 0·75 to 90. The complete equation obtained was :—

$$\frac{hD}{k} = 0{\cdot}024 \left(\frac{DV\rho}{\mu}\right)^{0{\cdot}8} \left(\frac{c\mu}{k}\right)^{0{\cdot}4}$$

This equation had previously been obtained by Dittus and Boelter,[19] who also obtained the following equation for cooling fluids in turbulent flow in pipes :—

$$\frac{hD}{k} = 0{\cdot}026 \left(\frac{DV\rho}{\mu}\right)^{0{\cdot}8} \left(\frac{c\mu}{k}\right)^{0{\cdot}3}$$

McAdams[20] reviewed the data of a number of investigators on air, CO_2, coal gas, steam, water, acetone, benzene, n-butyl alcohol and petroleum oils, and recommended for heating and cooling the equation :—

$$\frac{hD}{k} = 0{\cdot}0225 \left(\frac{DV\rho}{\mu}\right)^{0{\cdot}8} \left(\frac{c\mu}{k}\right)^{0{\cdot}4}$$

the fluid properties are taken at main body average temperature.

Gases.—The value of the group $\frac{c\mu}{k}$ varies very slightly from one gas to another and for different temperatures and pressures, and there is little opportunity to determine by experiment whether or not it enters. Values of $\frac{c\mu}{k}$ for gases at 60–80° F. and 1 atmosphere absolute, expressed in consistent units :—

Helium	0·695	Nitric oxide	0·755
Argon	0·668	Carbon monoxide	0·775
Hydrogen	0·735	Carbon dioxide	0·840
Oxygen	0·736	Ethylene	0·800
Nitrogen	0·733	Methane	0·781
Air	0·733	Steam at 300° F. and 1 Atm.	1·20

Fig. 7 shows some of the available data for gases. The upper line represents McAdams' equation when the average value of 0·73 has been substituted for $\frac{c\mu}{k}$ giving :—

$$\frac{hD}{k} = 0{\cdot}020 \left(\frac{DV\rho}{\mu}\right)^{0{\cdot}8}$$

which is the same as the Prandtl-Taylor equation when m=0·3. For cooling superheated steam, the equation of McAdams with

[19] Dittus and Boelter, *Univ. Calif. Pub. Eng.*, 1930, **2**, 443.
[20] McAdams, " Heat Transmission," McGraw-Hill, 1933.

$\frac{c\mu}{k} = 1{\cdot}20$ gives values of h that are slightly lower, generally, than those calculated from the available experimental data.

Water.—Lawrence and Sherwood obtained extensive data on heating water which are in agreement with the equation of McAdams :—

$$\frac{hD}{k} = 0{\cdot}0225 \left(\frac{DV\rho}{\mu}\right)^{0{\cdot}8} \left(\frac{c\mu}{k}\right)^{0{\cdot}4}$$

the line drawn in Fig. 9 represents this equation.

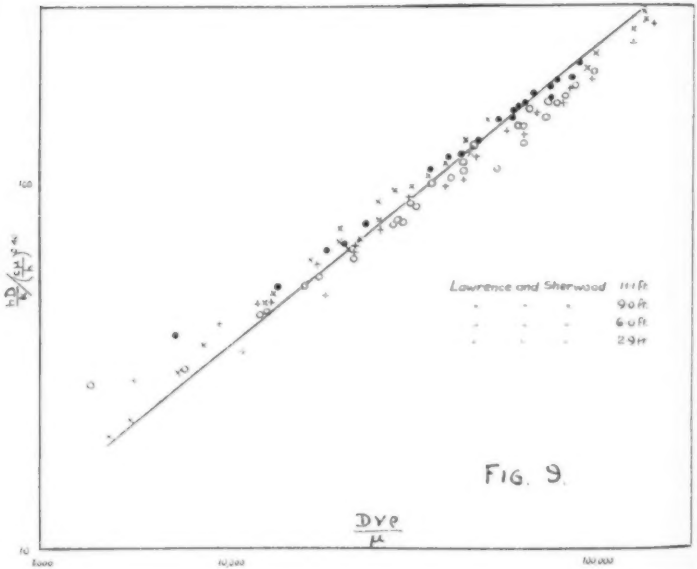


FIG. 9.

Oils.—With hydrocarbon oils, large variations in the value of the dimensionless group $\frac{c\mu}{k}$ occur, which makes it possible to determine the effect of this group on heat transfer. Morris and Whitman[21] made extensive experiments on the heating and cooling of oil in turbulent flow in a straight steel pipe 10 ft. long, with internal and external diameters of 0·62 in. and 0·84 in. The oils used were two gas oils (sp. gr. 0·841 and 0·846), two straw oils

[21] Morris and Whitman, *Ind. Eng. Chem.*, 1928, **20**, 234.

(sp. gr. 0·879) and a light motor oil (sp. gr. 0·917). Properties of the oil at main body average temperature were found to give better correlation of the data than at an average film temperature. Since $\frac{c\mu}{k}$ depends only on temperature for a given oil, heating runs were selected for each oil having about the same temperature. Let $\frac{hD}{k} = M$, $\frac{DV\rho}{\mu} = N$, and $\frac{c\mu}{k} = P$. Log M was plotted against log N for the selected runs, giving lines with slopes of about 1·02. Log $\frac{M}{N^{1\cdot02}}$ was then plotted against log P for all the heating data, including some for water, giving a line with a slope of about 0·5. Log $\frac{M}{P^{0\cdot5}}$ was now plotted against log N for all the heating data, and the equation best representing the curve drawn through the points obtained. Let this equation be $\frac{M}{P^{0\cdot5}} = \phi(N)$. Log $\frac{M}{\phi(N)}$ was then plotted against log P, and the whole process repeated until log $\frac{M}{\phi(N)}$ plotted against log P gave the same function of P as had been used for finding ϕ. The final equation obtained was :—

$$\frac{hD}{k} = \left\{0{\cdot}000016\left(\frac{DV\rho}{\mu}\right)^3 - 0{\cdot}017\left(\frac{DV\rho}{\mu}\right)^2 + 10{\cdot}8\left(\frac{DV\rho}{\mu}\right) - 53\right\}\left(\frac{c\mu}{k}\right)^{0\cdot37}$$

D is in inches and μ in centipoises.

When $\frac{hD}{k} / \left(\frac{c\mu}{k}\right)^{0\cdot37}$ was plotted against $\frac{DV\rho}{\mu}$ for the heating data, all the points lay on a smooth curve shown in Fig. 10. The data obtained for cooling were not as accurately correlated in this way. The curve recommended by Morris and Whitman retained the shape of the heating curve and was 25 per cent. below. McAdams[20] plotted the data of a number of investigators and recommended for $\frac{DV\rho}{\mu} > 9000$, the equation :—

$$\frac{hD}{k} = 0{\cdot}0225\left(\frac{DV\rho}{\mu}\right)^{0\cdot8}\left(\frac{c\mu}{k}\right)^{0\cdot4}$$

The values of $\frac{hD}{k}$ given by this equation are low. The line representing this equation is shown in Fig. 11, and the curve

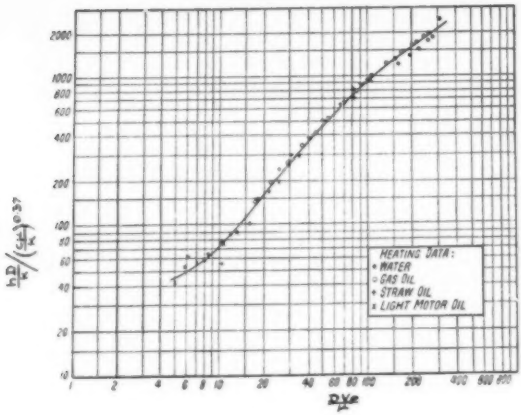

HEATING DATA:
• WATER
○ GAS OIL
+ STRAW OIL
× LIGHT MOTOR OIL

Fig. 10.

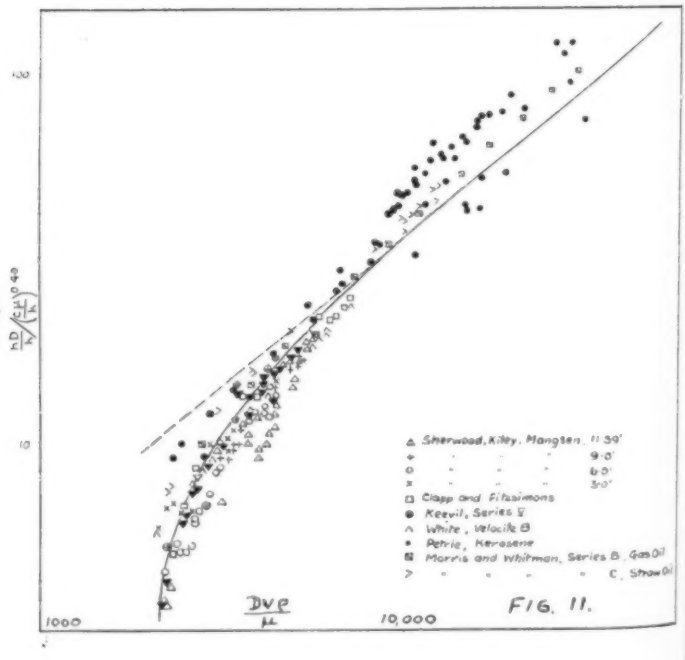

△ Sherwood, Kilby, Mangten. 11·39'
+ " " " 9·0'
○ " " " 6·0'
× " " " 3·0'
□ Clapp and Fitzsimons
● Keevil, Series S
∧ White, Velocity B
• Petrie, Kerosene
Morris and Whitman, Series B. Gas Oil
> " " " C. Straw Oil
1000
10,000

FIG. 11.

given by McAdams for values of $\frac{DV\rho}{\mu}$ less than 9000 is also shown. In Fig. 12 data for cooling oils in pipes are plotted and compared with McAdams' curves.

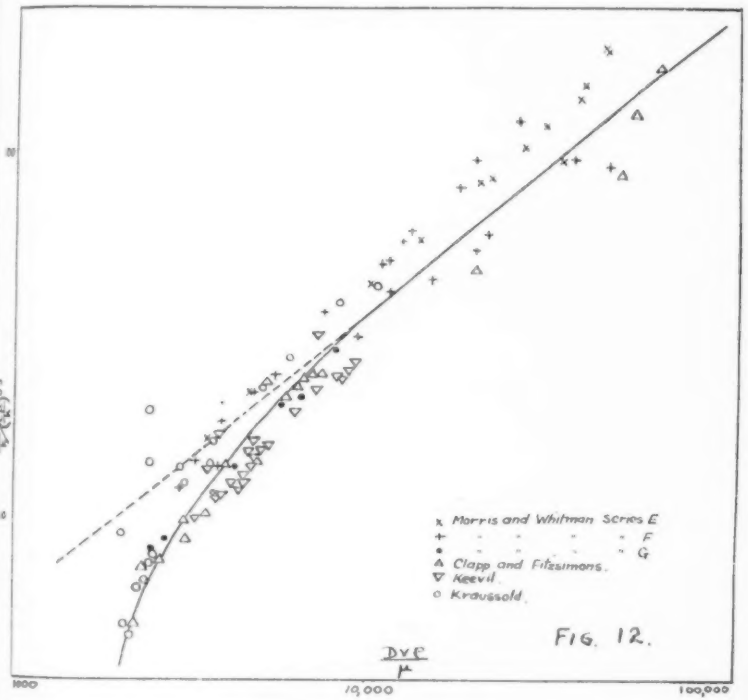


FIG. 12.

Miscellaneous Liquids.—The data of Sherwood and Petrie[12] for heating n-butyl alcohol, acetone and benzene are plotted in Fig. 13, and show that the equation of McAdams is in agreement with these experimental determinations.

TEMPERATURE.

Mean Temperature Difference.—When a fluid flowing in a pipe is being heated, the temperature difference between the fluid and the pipe changes continuously with the distance along the pipe. For heat transfer calculations a mean value of this temperature

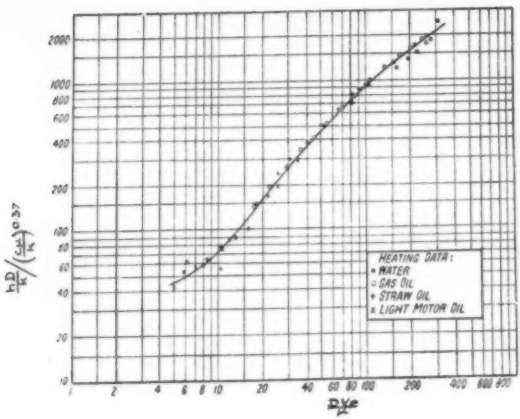
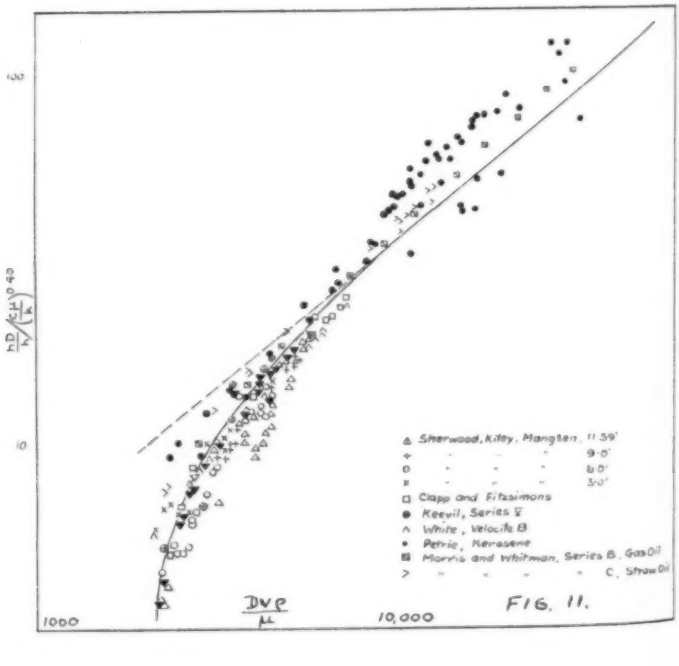

HEATING DATA:
• WATER
○ GAS OIL
+ STRAW OIL
x LIGHT MOTOR OIL

Fig. 10.


△ Sherwood, Kitty, Mangten, 11.59'
+ " " " 9.0'
○ " " " 6.0'
x " " " 3.0'
□ Clapp and Fitzsimons
● Keevil, Series V
∧ White, Velocity B
• Petrie, Kerosene
⊠ Morris and Whitman, Series B, Gas Oil
> " " " C, Straw Oil
1000
10,000

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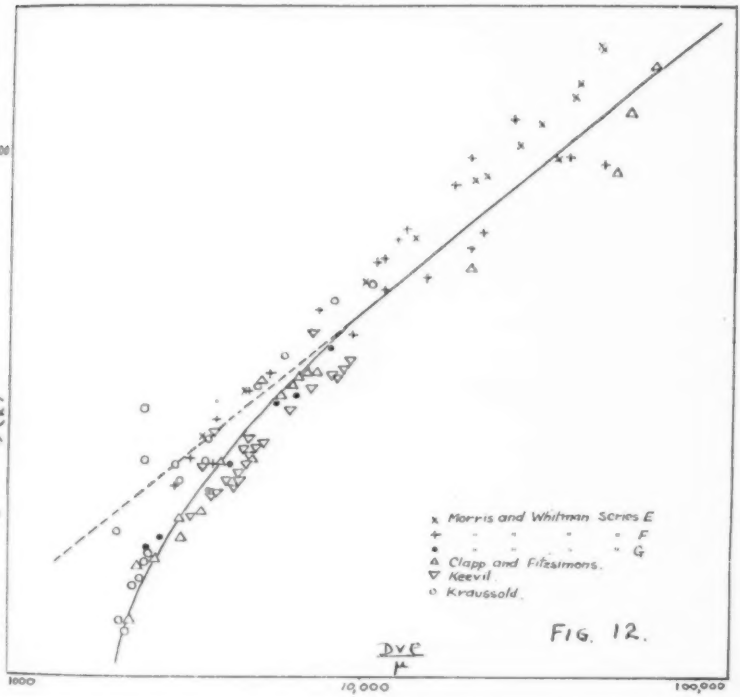

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TEMPERATURE.

Mean Temperature Difference.—When a fluid flowing in a pipe is being heated, the temperature difference between the fluid and the pipe changes continuously with the distance along the pipe. For heat transfer calculations a mean value of this temperature

difference is required. The temperature of the pipe may be constant or vary. Considering the case where T is the constant temperature of the pipe and W the weight of fluid flowing in unit time, let the average temperature of the fluid at a section along

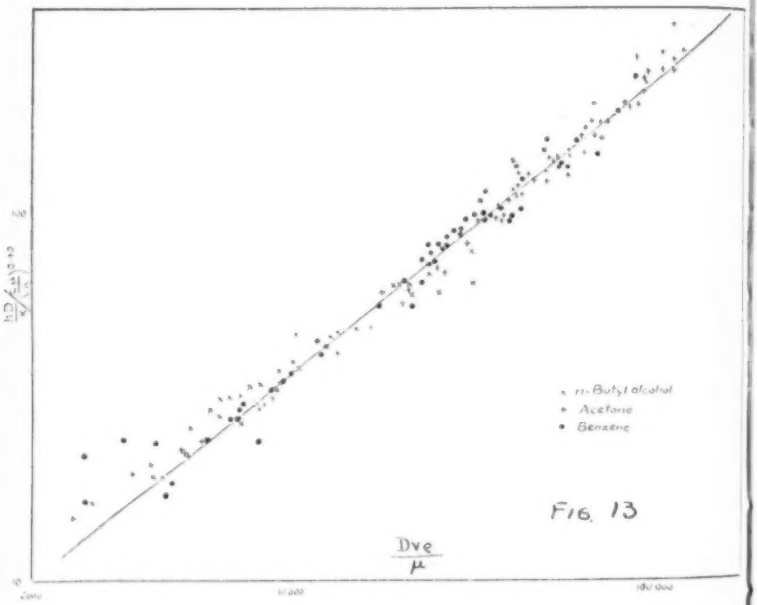

FIG. 13

the pipe be t ; let the temperature of the fluid be raised dt as it flows over an element of pipe surface, area dS, at the section under consideration. The heat absorbed by the fluid in a given time in flowing over the surface element dS is the same as the heat transmitted through dS in the given time, or

$$Wc\ dt = -h\ (T-t)\ dS.$$

Assuming that h and c remain constant for the whole length of the pipe, the total surface area of the pipe will be given by

$$S = \frac{Wc}{a}\ \log_e \frac{(T-t_1)}{(T-t_2)}$$

where t_1 and t_2 are the initial and final temperatures of the fluid. If the temperature difference between fluid and pipe was constant and equal to $(T-t)_{av}$ we should have

$$\{(T-t_1) - (T-t_2)\}\quad Wc = h(T-t)_{av}\ S.$$

Hence
$$(T-t)_{av} = \frac{(T-t_1) - (T-t_2)}{\log_e \frac{(T-t_1)}{(T-t_2)}}$$

For either counter or parallel flow of fluids in a perfectly insulated exchanger, in which changes only in sensible heat are involved, the decrease in T is proportional to the increase in t, and it can be shown that this equation is applicable, provided that the overall coefficient of heat transfer and the specific heat are constant. The specific heat of any fluid is, however, a function of temperature, and the heat transfer coefficient depends on physical properties of the fluid which vary with temperature.

For some petroleum oils the variation in viscosity, and consequently the heat transfer coefficient, with temperature is considerable. The use of the logarithmic mean temperature difference in such a case, with a big difference in temperature between entering and leaving liquid, would involve an erroneous rate of heat transfer. Considering the case where the pipe temperature remains constant, a heat balance over an element of area dS gives

$$Wc\ dt = -h\ (T-t)\ dS.$$

Assume the coefficient of heat transfer to be given by

$$\frac{hD}{k} = A\left(\frac{c\mu}{k}\right)^m \left(\frac{W}{D\mu}\right)^n \quad \text{Where A is a constant.}$$

The group $\frac{W}{D\mu}$ is obtained from $\frac{DV\rho}{\mu}$ since $\frac{DV\rho}{\mu} = \frac{D4W}{\mu\pi D^2} = \frac{4W}{\pi D\mu}$

Then
$$dS = -\frac{WcD}{Ak\left(\frac{c\mu}{k}\right)^m \left(\frac{W}{D\mu}\right)^n} \frac{dt}{T-t}$$

The thermal conductivities of oils vary very slightly with temperature. Their specific heats vary as a direct function of temperature, but the variation is not large. The viscosity-temperature relation is approximately $\mu = \alpha t^{-\beta}$, where α and β are constants depending on the type of oil.

Neglecting the variation in specific heat and thermal conductivity, and considering the viscosity at mean stream temperature

$$dS = \frac{A^1\ dt}{t^{\beta(n-m)}(T-t)} \quad \text{where } A^1 \text{ is a constant.}$$

With m=0·4 and n=0·8, β (n—m) may range from 0·36 to 3·8, depending on whether the oil is paraffin or asphalt base.

A difference of a few degrees in the temperature used may result in five or tenfold variation in viscosity with a corresponding error in the heat transfer coefficient calculated. The mean liquid temperature can be determined by graphical integration, from a graph of liquid temperature against pipe surface passed over,

when the approximate laws of variation of heat transfer coefficient and specific heat are known.

$$\frac{h}{c} = B\,\phi\,(t).$$

Where ϕ is some function of the liquid temperature and B is a constant. ϕ can be obtained experimentally or calculated from the viscosity-temperature and specific heat-temperature curves for the oil using :—

$$\phi\,(t) = c^{1-m}\,\mu^{n-m}.$$

A series of values of $\phi\,(t)\,\frac{\Delta t}{T-t}$ are calculated and plotted for close temperature intervals Δt, over the required range. Graphical integration gives the liquid temperature curve. In practice the plotting of the differential curve is omitted and stepwise integration by Simpson's rule carried out simultaneously, giving directly the liquid temperature curve. The method is also applicable to the case of two liquids changing temperature from end to end.

Radial Temperature Gradient.—The effect of the radial temperature gradient on the properties of the fluid has been neglected in the derivation of theoretical equations ; consequently these equations can only be true when there is a very small amount of heat transfer taking place or when the properties of the fluid do not vary with temperature. In applying these equations, since the greater part of the thermal resistance is in the boundary layer, investigators have used a mean film temperature at which to take the properties of the fluid.

In order to obtain an equation to fit experimental data it is necessary to use the temperature which gives best correlation. Many investigators found that properties at mean stream temperature correlated their data better than film properties. The use of mean stream temperature has the advantage that no trial and error method of calculation for design purposes is necessary.

The great majority of the available data on heat transmission to fluids has been obtained using low pressure steam as the heating medium, and consequently with little variation in tube wall temperature. The true effect of temperature cannot be determined until experiments have been carried out varying liquid and tube wall temperatures.

The main difficulty to be overcome in order to elucidate the laws of heat transmission in turbulent flow is the determination of the velocity and temperature distributions under varying conditions. When the laws governing the variations of distribution are known, it merely remains to form the differential equation and obtain from this the required equation for heat transfer.

Salt Domes*

By R. V. Browne (Student).

Although salt domes have been known or inferred for many years, it is only from 1900 onwards that a serious interest has been taken in them. In the Gulf Coast district of America, the presence of masses of salt below the surface of the earth, although probably suspected for a considerable time beforehand, was not definitely proved until 1862; when, in deepening an old brine well at Petite Anse, Louisiana, massive rock salt was discovered, which was found subsequently to be part of a large stock underlying the district.

Mining for the salt followed, and thus was taken the first real step towards a knowledge of the structure of the North American salt dome. It was not long before the presence of paraffin dirt and methane in the vicinity of the salt, led prospectors to drill wells in the hope of discovering oil. In 1901, A. F. Lucas was entirely successful in this respect. While drilling at 1139 ft., his well blew in with an enormous production which was estimated at 75,000 barrels per day.

The connection with profitable oil accumulations being thus established, the interest in these salt structures was stimulated. Comparatively few, however, were discovered until 1926, when, with the advent of geophysical means, the number of known salt domes was soon tripled. Indeed the discovery of thirty-three new salt dome prospects in 1928, due chiefly to geophysical methods, stands out as a remarkable achievement.

Although America is the most fortunate in what might be called the economic side of salt domes, these structures have been known and studied in other parts of the world for many years. Germany, Persia, Iraq, Rumania and Arabia are the chief areas where salt domes have been found, one only having been reported from Siberia.[1]

Surface Features.

America.—The physiographic expression of the Gulf Coast salt domes depends largely on the proximity of the salt to the surface, the character of the overlying or neighbouring sediments, and the amount of uplift.

A period of gradual uplift has continued until recent times, and in many cases the movement is still going on. Where the domal materials are close to the surface, and the forces have been locally more intense, a development of mounds or ridges has resulted. The

* Paper submitted for Students' Medal and Prize, 1931–32. Commended.

[1] *Econ. Geol.*, 1926, **21**, 774–781.

shape and position of these mounds usually bear a general relationship to the shape and position of the underlying dome, the diameter of the mound being approximately the same as that of the salt core. Where the domal materials are deep seated these features are usually absent, although in some instances this absence may be due to erosion.

In small areas in the north of this district, Cretaceous rocks outcrop and the structural disturbance is thus visible at the surface. In the main, however, the district is composed of unconsolidated Tertiary and Quaternary sediments, and here the domes are indicated mainly by topographical irregularities. Of these, the chief are :—

(1) Topographic domes ranging from those which are hardly discernible to the eye, up to mounds 100 ft. or so high which rise from the flat surrounding plain.
(2) Sunken areas or small lakes often surrounded by a circle of low hills.
(3) Salt licks and springs of salt, acid, or sulphur water are fairly common.
(4) Where outcrops of rocks can be studied, they are usually found to be tilted steeply, or of a formation older than is usually found in the district.

D. C. Barton,[2] describing topography of Type 2, states that three hypotheses can be brought forward to explain it :—

(*a*) It is the result of the warping of the present land surface.
(*b*) It is the result of the differential erosion of beds already having a domed structure.
(*c*) The central basin is due to collapse of the surface consequent upon the solution of the top of the salt core.

Persia.—In the bare, waterless landscape of Laristan, the salt-plugs introduce sharp discordances of topography. The chief physical features formed are[3] :—

(*a*) Salt Hills. When the salt has broken through in recent times and its sheath of sediments is intact, it builds up a mountain which has a shape reminiscent of a stick of shaving soap. When erosion commences, and the girdle of sediments breaks down, the salt usually weathers into a gentle domal hill. Differential erosion within the salt usually gives rise to fantastic pinnacles of the materials more resistant to weathering, such as dolomite or dolerite. When the encircling sediments are weathered away entirely, the salt hill rises steeply on all sides from the weathered back rim of sediment.

[2] Barton, " Geology of the Salt Dome Oilfields," p. 724.
[3] Harrison, *Quart. J. Geol. Soc.*, 1930, **86**, 463–520.

(*b*) Salt Glaciers. When the horizontal movement of salt is unrestricted, it tends, under the action of gravity, to flow to regions of lower level. This may be accomplished through a breach in the rim of sediments, the salt then issuing as a gently inclined tongue, which in one case reaches a distance of three miles from the edge of the dome. When quite unrestricted it may flow away from the central plug in all directions as an apron-like sheet. These flows "simulate somewhat the restlessness of an Alpine Glacier, sharp cracks are to be heard every few minutes and dislodged fragments come rattling down."

(*c*) Solution Cauldrons. These are negative features in which erosion has removed the soluble parts of the dome faster than the neighbouring sedimentary rocks, *e.g.*, the Zangur dome has a 4000 ft. central topographical depression from which the corresponding amount of salt has been dissolved.

(*d*) Salt Marshes. The flooding of streams which are strongly saline causes large areas in the plains to become permanently salty.

If the salt has not reached the surface and ground water has had a chance to erode it, the cover rocks, being thus deprived of support, cave in. The result, therefore, is a confused jumble of rocks above the salt plug.

The features cited above from America and Persia represent the two extremes of surface expression, the low mounds of the Gulf Coast being in marked contrast to, say, the Puhal salt plug, which forms a conspicuous mountain about 2190 ft. high. The topographical features in other countries, then, can be described with a fair degree of accuracy, as modifications of one or other of the examples given above.

An interesting feature is the "solution-grabens" of Germany described by Stille.[4] As a result of the sinking of the sediments overlying the salt, the Tertiary is found preserved there, whereas off the salt it has been more or less completely removed by denudation.

The Structure of Salt Domes.

The Source and Age of the Salt.—Geologists, in the main, now agree that the salt of salt domes is derived from thick beds of sedimentary origin. The special circumstances which are thought to have brought about the deposition of large masses of salts are as follows. An arm of the sea is cut off from direct connection with the outer ocean. The volume of water thus enclosed becomes stale, and with increasing evaporation and concentration the soluble

[4] Stille, "Geol. of the Salt Dome Oilfields," 149.

salts are thrown down. Calcium sulphate would be thus deposited after the less soluble calcium and magnesium carbonates, but before the more soluble sodium chloride. Van't Hoff has shown that if the temperature is not below 25° C., the form in which the calcium sulphate would be deposited is anhydrite. Inasmuch as this temperature would probably be reached by the evaporating waters in arid climates, the original precipitates of marine sulphates would be anhydrite, or layers of anhydrite and gypsum, the former predominating. When 93 per cent. of the water has been removed, rock salt is deposited. To keep up the supply of salts, periodic influxes of the ocean must occur, and thus we should expect to find layers of anhydrite interbedded with the main rock salt.

This state of affairs is well illustrated in the case of Kara Boghaz, an indentation on the Eastern shore of the Caspian Sea. Here, the bar between basin and open sea is only a few hundred yards wide and very shallow. Strong evaporation proceeds in the basin, the loss being supplied from outside by a current which flows in through the narrow strait.

The absence of fossils in the Stassfurt deposits of Germany must be explained if the hypothesis given above is correct. Walther believes that the salts were precipitated from a basin entirely cut off from the sea. On the other hand, by postulating an extended bar between basin and ocean, so that organisms have time to make good their escape, the absence of fossils can be explained.[5]

The age of the intruded salt has always been a difficult and controversial problem, only that of Germany being entirely free from doubt. The salt there is of Upper Permian (Zechstein) age.

A rather extreme view has been held by Voitesti[6] for some years. He believes that the salt belongs to no known marine or continental geological formation, and was precipitated on the first crust of the earth, in an atmosphere very rich in the vapours of chlorides and whose temperature was 700–800° C. By this means, he hopes to explain, "all the peculiar physico-chemical and mineralogical characteristics of the salt, as well as the widespread appearance of the salt domes on the whole surface of the earth, in a manner identical genetically and in most of the known geological formations." The objections to this hypothesis are many, and Voitesti's views are ably contested by Van der Gracht in the discussion which follows the paper cited.

The lack of positive evidence for the existence of bedded salt deposits beneath the Gulf Coast region of America has always been a stumbling block in the way of a final settlement of the origin

[5] Wallace, *Geol. Mag.*, 1914, p. 274.
[6] Voitesti, "Geol. of the Salt Dome Oilfields," 118.

of the American Domes. It has been the reason for the formulation of many theories in which the salt is regarded as non-sedimentary, most of them variations on the solution theory. The finding of fossil algæ and potassium salts in the core of the Markham, Texas, salt dome constitute positive proof of the sedimentary origin of the salt of salt domes.[7] The algæ are identical with those discovered in the Permian salt deposit, and it is therefore argued that the Gulf Coast salt is probably Permian. Prof. Schuchert, who has always believed that a lower Cretaceous age should be assigned to the salt, believes that something more dependable than algæ is necessary to determine the true age. The consensus of opinion, however, seems to favour a Permian or Triassic age for the salt. Sidney Powers[8] postulates a Permian salt basin on each side of the Sabine uplift. G. S. Rogers[9] also assumes Permian salt deposits beneath the Gulf Coast.

In Roumania, as in America, considerable controversy has raged over the age of the salt found there. It has been regarded as belonging to the Miocene Salifère, largely on the authority of Suess. The actual position of the salt masses, however, being due solely to tectonic causes, and not at all stratigraphical, makes a definite statement as to their age almost impossible. Basing their views largely on the fact that the Miocene is known to contain a saline facies outside Roumania, geologists still believe the salt to be of that age. Voitesti and Cunningham Craig[10] are opposed to this view, believing in an age older than Miocene. The more recent results of deeper and better drilling, however, are bringing about a more general agreement in a Permian age.

Those who have worked on the salt plugs of Persia assure us that the age of the salt is Cambrian or pre-Cambrian. Even here, however, there is a possibility that the Cambrian rocks brought up by the salt may have been picked up from overthrust nappes.

The Form of the Salt Mass.—Although the term "salt-dome" seems to have been used indiscriminately, it should really only be used for the extreme form of "salt anticline." That is, the salt may exist as a long ridge or anticline, perhaps only partially penetrating overlying beds, or as a more mature boss-like or mushroom-shaped mass, thrusting through many feet of sediments. These salt ridges range from flat to sharp and stometimes overturned ridges, which may extend for many miles. This type of structure is well brought out in many of the occurrences in Europe and Mexico. The plug-like form, characteristic of the domes of the

[7] De Golyer, Ibid., p. 781.
[8] Powers, Ibid., see plate to face 214.
[9] Rogers, *Econ. Geol.*, 1918, **13**, p. 476.
[10] Voitesti, *J. Inst. Petr. Techn.*, 1923, **9**, 291–300.

Gulf Coast and Persia, may be sharp or flat topped, nearly circular or elliptical in horizontal section, and varying from a fraction of a mile up to three miles across.

The salt of the German basin shows both these types. As well as the normal bedded phase which is found on the margin of the basin, the following types of salt domes and salt ridges can be recognised.[11]

(*a*) Stassfurt type—broad anticlinal folds with a thickening of salt along the crest.

(*b*) Asse type—the salt only partially piercing the overlying beds along small fissure zones.

(*c*) Leine type—a broken anticline with salt squeezed up between the two flanks.

(*d*) Hanoverian type—the true salt plug, with complicated internal folding and flanked by steeply dipping and sometimes overturned beds. In extreme cases the salt stock may be severed entirely from its source bed, terminating in a point at its lower end and standing as an isolated mass of salt floating in younger formations. If movement of the salt has ceased, underground water may leach out the salt to a more or less flat plane, the so called "Saltzpiegal" or salt table. The salt table in Hanover lies at a depth of one hundred to two hundred metres.

The Rumanian salt domes seem to be characterised by an overturning in their upper part, and some are thought to exist as an uprooted core or klippe, due to extensive underthrusting.

An interesting feature of the American domes is presented by the results of wells drilled on the Barbers Hill dome, Texas. After penetrating considerable thicknesses of salt—1888 ft. in one case—the regular succession of Tertiaries was again encountered, which showed a large oil production. The conclusion reached was that the dome was in the form of an inverted cone, at least in the upper part of the intrusion. It is possible that other domes may have the same shape. Owen[12] states that it is extremely improbable that a cylindrical or acute conical mass of the intruded material could be formed. He visualises the salt as an inverted cone, but with jagged sides. If this is so, large areas previously believed condemned because test wells drilled into the salt will be redrilled in an effort to obtain production below the overhang. Whether improved geophysical methods and the interpretations thereof will shed any light on the problems remains to be seen.

The salt itself is not entirely homogeneous. It is usually found to have bands of a darker coloured material which have proved in

[11] Barton, Op. cit., p. 190.
[12] Owen, *J. Inst. Petr. Techn.*, 1931, **17**, 337.

the case of the American domes to be composed of minute particles of transparent anhydrite which absorb the light. By means of these bands, the tectonic structure of the mass can be studied. Their complex folding and contortion into countless anticlines and synclines, as well as shearing and fracturing, indicate a true flow structure. They also show the intense compression that the salt has undergone.

As we have already said, the salt is a sedimentary deposit, and in the case of the German domes the stratigraphical succession can be correlated exactly with the undomed Permian salt. In the search for potash, extensive folding of the beds, often of an isoclinal type, was revealed.

In addition to the salt, the domes often contain interbedded anhydrite, gypsiferous clays, marls, etc. The salt is often remarkably pure, containing up to 99 per cent. NaCl.

The Cap Rock.—The top of the salt mass is succeeded in many instances by a characteristic series of rock materials known collectively as the " cap rock." In the main, this cap is composed of calcite, gypsum, and anhydrite, in descending order, associated with other minerals of which sulphur, pyrite, and barite are the most common. It may occur as a tip or wafer, covering only the top of the salt stock, as is usual in the American examples ; or it may extent for some distance down its sides, examples of which are found in Mexico and Germany. In thickness it may range up to 1000 ft.

There has been much speculation as to the origin of the anhydrite of the cap rock, the main theories being :—

(*a*) It is the residuum of anhydrite originally interbedded with salt, circulating waters having destroyed the salt.

(*b*) It is part of the bed of anhydrite which overlay the sedimentary salt, the intruding salt having brought it up from depth.

(*c*) It is a deposit from solution.

Both theories (*a*) and (*b*), then, regard the anhydrite as sedimentary, the divergence being that in the former it is regarded as being secondarily formed by cementation of sedimentary anhydrite, freed from the salt stock by solution of the more soluble materials ; while in the latter it is thought to exist as an original sedimentary bed.

The evidence favouring sedimentary origin is as follows :—

(1) Breccia fragments have been examined of which the lamination was so perfect as to leave no doubt as to their sedimentary origin.[13] There is no evidence of the banding being due to flowage, shearing or diffusion.[14]

[13] Goldman, *Bull. Amer. Assoc. Petr. Geol.*, 1931, **15**, 524.
[14] Goldman, " Geol. of the Salt Dome Oilfields," pp. 51–62.

(2) The presence of syngenetic dolomite, glauconite, celestite, and barite, all of which are regarded as characteristic of marine facies.

(3) Microscopic examination of the anhydrite shows it to have the character of sedimentary anhydrite prior to physical distortion. It is shown as a mass of rectangular euhedral grains.[15]

The residual theory first postulated by European geologists presents no difficulty when applied to the German salt domes. The "salt table" cuts off all the beds in the salt stock, setting free the solid beds of anhydrite which are known to occur abundantly in the salt. The weakness of this theory, when applied to American salt domes, is that very little anhydrite is known to occur in the salt there. No such beds as are found in Germany have been encountered in drilling. The proportion of anhydrite derived from the thin black bands in the salt, already described, would be relatively slight. The amount of solution, therefore, required to form the cap would seem excessive. Goldman[16] calculates that a removal of a column of salt, 1000 ft. high, would account for only 120 ft. of the 1050 ft. of anhydrite cap rock of the Clay Creek salt dome. He points out, however, that these figures apply to a static salt core. The entire thickness of the cap rock may be accounted for either by the mutual cancellation of upward movement and downward solution, or by solution, perhaps at the surface, before deposition of the beds now resting directly on the cap rock.

Both Chapman[17] and Vaughan,[18] however, note that the rock salt may contain, in some localities, more anhydrite than usual. Vaughan also states that when the salt is pure there is practically nothing that can be called true cap rock. This is found in three of the "Five Islands" of Louisiana. In another case, where the salt is impure, there is considerable cap rock present, the material of which is essentially the same as the impurities in the salt.

Goldman, after an examination of the material from the contact zone of anhydrite and salt, favours the assumption of the residual theory. A specimen from the shaft at Hockley shows good, roughly horizontal, parallel banding, the lower band being an intimate mixture of salt and anhydrite crystals, this being the layer in which the removal of salt and the cementation of anhydrite is not complete. It must be stated, however, that according to Prof. L. S. Brown,[19] the contact described above illustrates "a

[15] Brown, *Bull. Amer. Assoc. Petr. Geol.*, 1931, **15**, 515 and Fig. 20.
[16] Goldman, Ibid., 1931, **15**, 1105.
[17] Chapman, Ibid., 1926, **7**, 297.
[18] Vaughan, "Geol. of the Salt Dome Oilfields," p. 393.
[19] Brown, Op. cit., p. 528.

change of facies in a comfortable series and the presence of small quantities of the opposite mineral through a short distance on each side of the contact is to be expected."

Associated with the question of the solution of the salt by water is the phenomenon of the production of the "salt table" or flat salt-anhydrite contact. A contact produced by solution would tend to be irregular and unsymmetrical. Goldman states that the solution of the top of the salt core could be effected by the presence of permeable, water-bearing beds in the formations penetrated. Salt domes are known to be associated with peripheral faults.[20] These faults would provide a passage for circulating water, and although solution controlled in this way would probably not produce flat salt tables, it may have been a factor in the general lowering of the top of the salt core.

Prof. Brown, whose work has already been mentioned, seems to be the chief exponent of the origin of the cap rock as due mainly to upthrust; the movement continuing, if not originating, long after the crystallisation and consolidation of the cap rock minerals. The evidence of movement is found in the extensive brecciation, faulting and slickensiding, as well as the mashed and gneissic structure exhibited by the cap rock. He also speculates on the age of the anhydrite, claiming it to be of Glen Rose age, his hypothesis being that celestite, which occurs in that formation, is also found in the cap rock. His evidence of intense brecciation in the upper part of the cap, and a least altered phase at the base could be explained quite well by the residual theory. The upper part of the cap would be the oldest and the most altered physically and chemically, the base being the youngest and least altered.

We now turn to the consideration of theory (c), that is, the assumption that the anhydrite is secondary and not primary. This has been discussed by De Golyer,[21] Rogers[22] and Murray Stuart.[23] De Golyer bases his theory on the studies of F. K. Cameron, who in his investigations into the solubility of calcium sulphate in aqueous solutions of sodium chloride, found that at a certain concentration of NaCl (129·5 grms./litre) the solubility of $CaSO_4$ is a maximum. Further increase in the concentration of NaCl would cause a deposition of the $CaSO_4$. He suggests, therefore, that the cap rock was formed by precipitation resulting from an increase in salt content of a solution containing calcium sulphate, on coming into contact with, and dissolving part of, the salt stock of the dome; or, reacting with strongly saline water

[20] Carlton, "Structure of Typical American Oilfields," Vol. II, p. 460; also Sidney Powers, Op. cit., p. 528.
[21] De Golyer, *Econ. Geol.*, 1918, **13**, 616–620.
[22] Rogers, *Econ. Geol.*, 1919, **14**, 178–180.
[23] Murray Stuart, *J. Inst. Petr. Techn.*, 1931, **17**, 338–345.

circulating round the dome. Rogers agrees with this view, but adds that the normal Gulf Coastal Plain waters, at least to a depth of 1800 ft., are extremely poor in sulphates; none of the East Texas waters carrying more than 2 grms./litre $CaSO_4$. He states that to precipitate $CaSO_4$ when saturated with NaCl they would have to carry more than 5 grms./litre. Deep waters, however, may conform to these conditions.

Murray Stuart, however, regards the soluble sulphates—*e.g.*, $MgSO_4$—as supplying the sulphate radicle, and lime-bearing waters the calcium, in the formation of calcium sulphate. Practically all naturally occurring rock salt contains soluble sulphates, and practically all meteoric waters contain calcium carbonate in solution. When these meteoric waters, percolating downwards, come in contact with waters containing the soluble sulphates leached from the dome, calcium sulphate is bound to be formed. The effect of both pressure and temperature would be to favour its deposition as anhydrite. His arguments are substantiated by examples from Roumania. The salt domes there are composed of remarkably pure salt, containing practically no soluble sulphates. According to theory, therefore, no cap rock could form over them, a fact which is borne out by observation. The only exception to this seems to be where the salt contains sulphide of iron as on the Bahadur Khel Salt Field of India. Here the sulphuric acid liberated from the iron sulphide, reacts with the salt to form sodium sulphate, and with calcium carbonate to form selenite.[24]

The presence of gypsum at a depth of more than 1000 ft. requires explanation. According to theory gypsum would be converted into anhydrite below a cover of 500 ft.[25] This interference with the normal pressure effect is explained by the fact that the gypsum forms more abundantly along lines of weakness such as shear surfaces, fissures and faults. It apparently forms most readily in the upper part of the anhydrite where fissures are numerous, although near faults it occurs abundantly at depth in the anhydrite zone.[26] It may be observed forming directly from anhydrite, with large areas in optical continuity.

The calcite which is found most commonly in the upper part of the gypsum-anhydrite cap, is now generally accepted as secondary. Its origin has been attributed to either :—

(*a*) An alteration product of anhydrite or gypsum, formed by their reaction with organic material, such as petroleum, sulphur also being formed in the process.

(*b*) As a deposit from percolating meteoric waters.

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[24] Murray Stuart, "Records Geol. Survey," India, 1919, **50**, 61–93.
[25] Newland, *Econ. Geol.*, 1921, **16**, 395.
[26] Goldman, *Bull. Geol. Soc. Amer.*, 1929, **13**, 40.

The first of these has many supporters, although direct proof of such a reduction is lacking. Experimental evidence however, is furnished by Cadman,[27] who, by passing natural gas, free from hydrogen sulphide, at moderate temperatures over anhydrite heated to dull redness, obtained an immediate evolution of H_2S. In addition, H_2O and CO_2 and an unsaturated hydrocarbon were evolved, and a mixture of CaO and CaS remained. The reaction therefore, is not by any means explained by the simple equation

$$CaSO_4+CH_4=CaCO_3+H_2S+H_2O$$

advanced by Hoppe-Seyler. The sulphur is generally accepted to have been formed by the oxidation of the hydrogen sulphide. The heat observed by De Golyer[28] in the Mexican domes is thought by him to be due, in part at least, to chemical reactions. If we apply this mode of origin to the case in point, such a reaction would occur at the edge of the cap rock, where it would be in contact with sedimentary beds containing hydrocarbons. The calcium carbonate plus hydrogen sulphide, or sulphur, must then be assumed to be carried into the cap rock in solution. All such reactions require conditions of high temperature and comparatively low pressure. Such an environment is not in agreement with the generally accepted modes of development of salt domes, and we must therefore accept with caution the implication of calcite and anhydrite in intimate association above anhydrite adjacent to beds containing abundant hydrocarbons.

Turning therefore to another possible source for our calcite, we have the possibility of its deposition by carbonate containing waters, percolating downwards, encountering the soluble salts leached from the dome. A layer of calcite would be deposited over the gypsum above the level reached by the dissolved sulphates. Alternatively, the water taking into solution the calcium sulphate, calcium carbonate, and the sulphur of the anhydrite cap would redeposit them in that order of deposition. Prof. Brown's work, in which he found what he thought to be primary sulphur in the cap rock, that is sulphur which existed prior to crystallisation of the anhydrite, appears to substantiate this last theory.

The great diversity of opinion on the origin of cap rock makes it extremely difficult for students to form any definite opinion on the subject. Difficulties are encountered which cannot be explained away, in every theory so far put forward. Petrological evidence is construed by geologists in different ways. The arguments put forward for the intimate intergrowth of salt and anhydrite in the specimen from Hockley already mentioned, illustrate this point.

[27] Cadman, *J. Inst. Petr. Techn.*, 1925, **11**, 487–489.
[28] De Golyer, *Econ. Geol.*, 1918, **13**, 299.

Such evidence, therefore, must be considered in relation to the broader, physical, chemical and geological, requirements of the problem if satisfactory solution is to be obtained. Further research into the question is obviously indicated.

The Mechanics of Salt Dome Formation.

The origin of salt domes has been a favourite and fruitful subject for speculation and controversy among geologists for many years. Theories have been advanced, attacked and rejected in turn; American literature of the present century being especially prolific in such contributions. It is not the object of this paper to deal with such theories as : deposition from solution, uplift by the force of growing crystals, and other similar ideas, which have now been abandoned, but to consider the structural or salt flowage theories, first advanced in Europe and now generally accepted.

Any theory must consider and satisfy the following points :—

(1) The source of the salt and the manner in which it has attained its present position.
(2) The doming, and sharp local uplift of the sediments surrounding the salt core.
(3) The source and relations of the anhydrite, gypsum, limestone and sulphur of the cap rock.
(4) The alignment of the domes and their relationship to the main structural features of the region.
(5) The origin, and mode of accumulation of the oil.

Briefly, the intrusive theory, now widely accepted, postulates a bedded salt deposit at depth, which, either by the force of orogenetic movements or isostatic adjustments, has been intruded in a plastic or semi-plastic condition upwards through the overlying beds.

Numerous experiments have been performed in connection with the plasticity of rock salt. The results vary widely and are not conclusive. A communication regarding the plasticity of salt in the Alsace mines is cited by Lees.[29] A figure of 150 Kg./cm. is stated as the pressure at which the salt passes from a brittle to a plastic state. Ewald and Polanyi[30] showed that the breaking load of rock salt was increased ten-fold when it was immersed in water, which effect ceased when the surface was dried, or the water saturated with salt.

If we recognise the importance of the time factor, the high temperatures and pressures reached below ground, and the presence of water with the salt, the force necessary to make salt plastic is probably much smaller than that indicated by laboratory experiments.

[29] Lees, *J. Inst. Petr. Techn.*, 1931, **17**, 274.
[30] *Nature*, 1924, pp. 766–767.

The theory that the sedimentary salt was first fused by heat due to vulcanicity has been suggested, but there is little support for such a hypothesis. Among the objections are[31] :—

(*a*) No positive evidence of volcanic activity in the salt dome regions of North America.

(*b*) No important salt deposits ascribable to volcanic origin are known in the world.

The evidence, therefore, points to the salt at depth as being extremely incompetent, and mobile enough to be set in motion by the forces which act upon it. Such forces, whether isostatic or orogenetic, will cause a flowage from areas of high pressure to those of low pressure.

The experiments of Torrey and Fralich,[32] Escher and Kuenen,[33] Link,[34] and others have demonstrated the formation of salt structures in miniature under laboratory conditions. The results obtained furnish additional evidence to substantiate the intrusive theory of salt dome origin. The result of lateral pressure upon a plastic layer interbedded with compact sands or sands cemented with plaster of Paris was :—

(*a*) A low anticline was formed but rapidly broken up into blocks similar to those observed in the structures of N.W. Europe. Continued pressure caused a thrust fault to form, which forced the plastic layer upwards at the place where the anticline was first formed—*i.e.*, the formation of the anticline relieved the confining pressure to such an extent that the incompetent bed was thrust upwards.

(*b*) Under extreme pressure the intrusion may be completely separated from the original bed.

(*c*) The dip of the beds in close proximity to the ascending mass was high.

(*d*) The movement of a plastic bed is dependent on the relative competency of the beds overlying and underlying it.

The principal results of the experiments of Escher and Kuenen, in which alternating layers of paraffin and clay were deformed by pressure from below, due to a ring shaped disc, were that : "All the shapes of the folds observed in German salt domes can be completely explained by Lachmann's theory—*i.e.*, by the isostatic pressing up of specifically lighter salt in pillar-like masses. This alone, however, does not exclude the possibility that tangential pressure may be partly or entirely responsible for the known

[31] De Golyer, "Geol. of the Salt Dome Oilfields," p. 33.
[32] Torrey and Fralich, "Journal of Geology," **34**, 224-234.
[33] Escher and Kuenen, "Experiments in Connection with Salt Domes," reviewed by D. C. Barton, *Bull. Amer. Assoc. Petr. Geol.*, 1930, **14**, 107.
[34] Link, *Bull. Amer. Assoc. Petr. Geol.*, 1930, **14**, 483–503.

phenomena." The conditions of the experiment, however, did not simulate the geological conditions of the salt anticlines or faintly diapiric salt dome ridges.

Although salt domes the world over seem to conform to certain specifications, their different geological history and environment makes a general statement on their origin extremely difficult. The views on the modes of origin in the various countries will, therefore, be treated separately.

Germany.—The two periods of post Zechstein earth movement —namely, the Rhenish (N.-S.) and the Saxon (W.N.W.-E.S.E.) seem to have a pronounced affect on the alignment of the domes. The tendency is for the domes to be associated with zones of uplift along these two tectonic lines. The absence of sharp folding away from the neighbourhood of the domes implies only a mild tangential force having affected the salt. Stille,[35] who in 1925 attributed them entirely to lateral compressive thrust, states in a later work that " in Germany the predominant force has been that of folding, but certainly in many places isostatic forces may have taken a part, and probably a larger part than the writer formerly was willing to admit."[36]

Furthermore, and this is very important, as the zone of uplift is traced into the interior of the North German basin, so do the salt structures tend to change from salt anticline to salt stock. The form of the dome, therefore, seems to have a direct connection with the weight of overburden deposited above the salt. Stille[37] puts forward the idea that the north east movement of the Rhenish mass gave rise to an easterly force in the south, a north easterly force in the north, plus a southward component on the north. These forces disrupted the subsurface forming zones of tension into which the salt, already under lateral compression, or under pressure of the overburden, would advance. It appears then, that the salt rendered plastic by pressure, sought an area of low pressure, such as a tension crack, fracture zone, intersection of two lines of weakness, etc. By how much its passage upwards was assisted by lateral pressure is not yet clear. It is probably, however, that the main effect of such pressure was the alignment and distribution of the domes, the important part of the motive force being supplied by the pressure due to overburden. Where the sediments above the salt are only moderately thick, and are composed of moderately consolidated beds, they have been domed but not pierced by the salt. The result is a salt anticline with the flanks of the salt concordant with the flank beds. Where the

[35] Stille, " Geol. of Salt Dome Oilfields," pp. 154–162.
[36] Stille, *Bull. Amer. Assoc. Petr. Geol.*, 1932, **16**, 177.
[37] Stille, Ibid., p. 176.

sediments are thick and relatively unconsolidated, penetration has taken place, the salt being stock-like in form.

America.—In comparing the salt domes of the Gulf Coast with those of Germany, two main problems present themselves. They are the absence in the former of :—

(*a*) A mother bed of salt ;

(*b*) Lines of weakness such as folds or faults.

The first of these has already been discussed.

The American domes occur in a region where lateral folding has not been manifest for a long way back in geological time. They are intruded through gently warped, relatively unconsolidated Tertiary sediments, which may be over 6000 ft. thick. The static thrust of this cover is not accepted as being, alone, sufficient to form the domes. De Golyer[38] believes that all the rocks of Cretaceous and older age were sharply folded before the Tertiary beds were laid down. The flowage of the bedded salt in the older rocks was therefore initiated. As the deposition of the Tertiaries went on, the more active salt cores were thrust upwards into this blanket of younger rocks. This process of deposition and flowage has persisted up to the present time.

Certainly many of the groups of salt domes lie in roughly straight lines with each other. A good example is the case of the domes known as the " Five Islands " of Louisiana.

A group of domes unrelated to those of the Gulf Coast appears in Texas. In a general way they appear parallel to the Balcones and Mexia fault zones. Fohs and Robinson[39] reach the conclusion that the domes also lie on a fault zone. They also put forward the hypothesis that, if the abrupt change which the Balcones fault makes from and N.E.–S.W. to E.–W. direction could be proved to be the result of the crossing of two fault lines ; it would be found that many of the coastal salt domes lie on the eastward extension of this E.–W. fault line. Lahee[40] writes, " Both the Mexia and Balcones lines of faulting are clearly related in origin to a single general cause, namely, the persistent sinking of a great geosyncline, the position of which is marked to-day by the Gulf of Mexico. This load of sediments will have tended always to slip away from the margins towards the centre of the basin, and marginal faults with a drop on the basinward side would result from such a tendency. But this sinking undoubtedly results in consequent buckling and upward reaction farther out in the basin. Concrete evidence of such upward movement is to be seen in lines along

[38] De Golyer, *J. Inst. Petr. Techn.*, 1931, **17**, 332 ; also " Geol. of Salt Dome Oilfields," p. 41.

[39] Fohs and Robinson, *Econ. Geol.*, 1923, **18**, 709–728.

[40] Lahee, *Bull. Amer. Assoc. Petr. Geol.*, **7**, 226–236.

which plugs of salt have been forced upwards in the central part of the basin."

The Mexican salt domes divide very nicely into two systems, one trending N.W.–S.E., parallel to the mountain front, and the other along a N.E.–S.W. line. There is no evidence, however, to show whether these lines, if they are lines of weakness, are folds or faults.

We may say then that the American salt domes are merely modifications of those of Germany, due to the difference of geological setting in the two countries. It is not clear whether very weak folding could be assumed to have taken place in America, which was sufficient to fold the salt, but not the overlying or underlying beds. On the evidence of Germany, where 2000 metres is taken as the minimum of overburden required for true doming, there is sufficient weight of sediments above the Gulf Coast salt to bring about this doming.

Persia.—An interesting feature of the Persian salt plugs is their indifference to recognisable zones of folding. Many are associated with anticlines, but they are often to be found on the pitching ends or flanks ; a few are situated in synclines. Their age of uplift is also independent, to some extent, to periods of folding. There appears, however, no evidence contrary to the fact that the domes might have been initiated along lines of earth movement, now obliterated, but oblique to present and later forces. The appearance of the plugs of synclines does not appear explainable in any other way, unless the lateral compression, which is greatest in deep-seated beds of such a structure, is a controlling factor.

Harrison[41] puts forward the theory that when folding of the beds occurred, the salt sought relief in the anticlinal arches, due to the increased load of sediments on the syncline. Thick nuclei of salt would thus accumulate and would be subjected to the static pressure equal to the excess of load on the syncline over that on the anticline, which he states to be about equal to 20,000 ft. of strata. Thus encouraged, the salt would pierce the points of weakness in the strata above it, quickly assuming a shape which would allow it to be driven upward with the least expenditure of energy.

Lees, on the other hand, calls upon no tengential pressure whatsoever for the formation of the plugs. An overburden of 2000 ft., he states, would be sufficient to render the salt plastic. When the formation is more deeply bedded, the extra pressure is sufficient to force the salt upward through the cover rocks.

The upward movement of the salt appears to have been spasmodic and to have accompanied the several earth movements which have affected the country since Mid-Cretaceous time. The

[41] Harrison, *J. Inst. Petr. Techn.*, 1931, **17**, 316–318.

intense folding and thrusting of Miocene and Pliocene times had the most pronounced effect on the movement of the plugs. Some, however, have moved at only one epoch, while others have continued in their movement until recent times.

Rumania.—The salt domes occur only in the Carpathian region proper, where they tend to align themselves along lines parallel to the front of the Carpathian overthrust. They are found in pronounced anticlines, never in synclines. The longitudinal faults which are greatly developed in this region have facilitated the intrusion of the salt. In the light of the geological history of the country, it is easy to call entirely upon orogenic thrust in order to explain the intrusions. Some believe that this thrust was a phase of the tangential forces which caused the overthrusting of the Carpathians. Against this view, however, is the objection that the mountain building forces had died out by Levantic times, whereas the salt outbreaks did not reach their maximum until Dacic times, continuing with undiminished force into Levantic times. Again, the intensity of the Carpathian folding increases from east to west. The intensity of the folds in the salt decreases from east to west. One explanation put forward, which is based on field evidence, is that the thrusting and folding started the upward movement of the salt, which was continued at a later date by the downward thrust due to the sediments above.

There is also the question of the shape of the domes. In many cases it seems to be influenced by tangential forces, being overthrust in the direction of the major movement. The question then arises as to whether they were originally normal domes which were subsequently deformed by earth movement. The fact, however, that salt domes are known which occur as isolated masses separated from their source beds, rather invites an explanation which assumes that the salt has been torn from its roots by pure thrusting and extruded into its present position. If this is so, the weight of the overburden would play a very subordinate part.

In attempting to sum up the case for the formation of salt domes, a problem to be faced is the relative importance of tangential pressure and weight of overburden. On this point writers differ considerably. Lees considers salt domes capable of being formed without any tangential pressure whatsoever, an overburden greater than 2000 ft. alone being sufficient. Romanes[42] calls upon a small tangential force plus an overburden of 6000 ft. Fulda[43] assumes an overburden of 11,000 ft. in conjunction with a large force which is necessary to drive the salt through the cover rocks, considerable horizontal movement taking place before it

[42] Romanes, Ibid., p. 258.
[43] Fulda, *Zeit. deut. Geol. Gesel.*, 1927, pp. 178–196.

moves in a vertical direction. Stille, at one time, offered tangential forces only as an explanation. Given a sufficiently large fracture above the salt, there is no reason at all why vertical stress of sufficient intensity should not force the salt into it. The fact that folding would probably cause such fractures rather suggests that the two forces work hand in hand. A small tangential pressure only is really necessary to orient and initiate the domes, the main upward driving force being then supplied by the weight of overburden.

The whole process would be greatly assisted by circulating interstital waters, which would take salt into solution at points of greater pressure and deposit it at points of release. These waters would be effective in carrying the salts upward under hydrostatic pressure, as well as acting as a lubricant around the borders of the salt core.

The Influence of Salt Domes on the Generation and Concentration of Petroleum.

Is the function of a salt dome as regards petroleum purely a structural one or has it played some part in the genesis of the oil? The following possibilities might be put forward for a genetic relationship :—

(1) The antiseptic and preserving properties of brine are well known, and it has been suggested that the salt water of the domes played a part in the suspension of decay of the petroleum-producing bodies and their subsequent conversion into oil.

(2) The uplift of the salt in its early stages produced shallow water conditions suitable for the development of oil-producing organisms.

(3) The high temperatures and pressures produced by the thrust of the salt through the formations might accelerate the generation of petroleum from source material.

The first of the above conditions suggests close association between brine and the petroleum source material. The conditions for the deposition of quantities of salt, and those for the accumulation of source material, whether animal or vegetable, appear incompatible. The conditions of Kara Boghaz, already mentioned, where organic material is swept into the brine basin, killed and probably preserved, appear exceptional.

Again, evidence can be brought forward to show that in Germany the formation of the oil was, in the main, pre-doming.

With regard to the third condition, oil is found in a dome such as Esperson, Texas, in gently arched Miocene sands, 2300 ft. below

the surface and 3000 ft. above the top of the salt. Below these sands there are 2500 ft. of gently folded beds of alternating sand and clay.

In the Gulf Coast the normal regional dip of 75–200 ft. per mile has been increased, in the neighbourhood of the domes, to a rise of sometimes 3000 ft. in three miles. If lateral migration of the oil has occurred, its movement would be naturally directed towards the centre of the uplift. Contrary views, however, have been put forward by those who believe that the enormous quantity of oil produced by the domes, together with the limited extent of structural disturbance, are evidence that the oil has migrated upwards from Cretaceous or older sands.[44] Such a migration was caused by the rupture of the oil-bearing formation of the intruding salt mass, allowing the oil to circulate freely around the salt core. If this is so, the flanking sand reservoirs would be filled first, with subsequent migration to porous cap rock or super cap sands. This transverse or vertical migration seems definitely to have occurred on the American salt domes. The common irregularity or occurrence of oils of different character in the flank-sand oil-fields strongly suggests migration along the faults or fractures which are usually associated with salt domes. Whether this type of migration is merely subordinate, the primary migration being lateral, is not yet clear.

Salt dome oilfields may be classified as :—

(1) Super cap fields.

(2) Cap rock fields.

(3) Flank-sand fields.

Type (1) is due to the uplift of the super salt sands, the oil being present due to simple anticlinal accumulation, under hydraulic head, in pervious sands between impervious clays. Type (2) is due to the high porosity of the limestone or dolomite, which forms the upper part of the cap rock. Impervious clays, lying unconformably on the cap rock, form the trap. Such fields are notable for their unrestricted flow, high recovery and short life. In type (3) the salt and oil sands are in fault contact, the salt being upthrown relative to the flank sediments. This type of trap, *i.e.*, a faulted zone with the down throw on the down dip side, is commonly regarded as most unfavourable for the efficient trapping of oil. The great effectiveness of this type on the Gulf Coast, however, is due to the sands being interbedded with a stiff, sticky clay. This clay has been dragged and plastered across the inner

[44] Jones, *Econ. Geol.*, 1918, **13**, 621 ; also Rogers, *Econ. Geol.*, 1919, **14**, 179.

edges of the faulted oil sands, thus forming a very efficient seal. This drag may also have pinched out the sands between the clay beds, forming what is, in effect, a trap of the lensing sand type. The preceding conditions also make for a fault which is closed horizontally, and thus the migration and escape of the oil is impossible.

The lateral distribution of petroleum around the dome is extremely irregular. Commonly only one quadrant of the domal area is productive. Local factors, such as porosity, radial faulting, lateral lensing and ineffective sealing, appear to have influenced the migration of oil to one sector rather than another.

In Rumania, where the oil producing districts have been strongly affected by the tectonics of the region, the oil deposits may be situated in asymmetric folds. In this case both flanks are productive the inverted one being, nevertheless, the richer in oil production, as well as having a greater lateral extent. When the folds have been overthrust the right flank is usually very poor, the inverted one only being productive. Great emphasis has been laid by Rumanian geologists on the influence of faults in the facilitation of the migration of the oil. Voitesti even favours the idea of the precipitation of the oil on the pre-Archean crust, and others favour a non-endogenetic source. In these theories the presence of faults is essential, the oil using the same fractures as the salt in the ascent to its present position. A final settlement of the question has not yet been reached.

Conclusion.

The early days of salt dome study were notable for a flood of irrational theories, in which the facts were made entirely subordinate to those theories. This flood has now subsided, and a more critical examination of the data provided has resulted in the sweeping away of all the speculative ideas in which so many people indulged.

The following points are now generally agreed to :—

(1) The salt of salt domes is derived from normal sedimentary saline deposits.

(2) The flow of the salt is due to earth pressure, aided possibly by circulating waters, intercrystalline solution and redeposition.

(3) Both tangential pressure and weight of overburden are responsible for salt dome formation. The relative importance of these two factors varies in different localities. In general, however, it may be said that while tangential pressure may

determine the orientation and initiation of the domes, the force which drove them upwards is mainly due to the weight of overburden. In Rumania the overburden appears to have played a subordinate part, the present position of the salt being due probably to pure thrusting.

(4) The origin of the cap rock is by no means clear. Further research is necessary before an agreed conclusion can be reached.

(5) There is only a faint theoretical possibility of a relation between salt domes and petroleum formation. Their effect is that of providing a structure which would greatly accelerate lateral migration, direct such migration towards the crest of the dome, and favour a general concentration of the oil in flank or cap.

REVIEWS.

ON THE MINERALOGY OF SEDIMENTARY ROCKS. A SERIES OF ESSAYS AND A BIBLIOGRAPHY. By P. G. H. Boswell. London: Thomas Murby & Co., 1933. Pp. ix.+393. 21s.

The practical application of sedimentary petrography to oilfield work during recent years has afforded a great stimulus to the theoretical study of this interesting and important subject, resulting in the appearance of several special text-books for the specific use of practical workers. A tendency has developed, however, to regard these condensed descriptive books as a sufficient source of information, and yet, in the course of the oil geologists' work, difficulties frequently appear which cannot be solved by reference to such text-books alone, and without a guide to the vast general literature of the subject it is often difficult or impossible to unearth references in a short time. Professor Boswell's book steps in here as such a guide. It will be a boon to geologists in general, but particularly to oil geologists who are more limited in time and opportunity for research in abstruse problems arising in the course of their applied scientific work.

The bibliography and abstracts, to deal with the second part of the book first, contain 1025 references, arranged alphabetically under author's names, to original work on sedimentary petrology and mineralogy; each reference is supported by a short synoptic paragraph.

Professor Boswell's claim to authority in his subject is amply demonstrated by the formidable list of references to his own contributions—numbering 37 in all and ranging through 20 years in time.

The first part of the book, occupying 127 pages, is devoted to eleven essays on particular aspects of the mineralogy of sedimentary rocks. The headings of these chapters are :—

I. Introduction.
II. History of Investigation.
III. The Individuality of Sediments.
IV. The Stability of Detrital Minerals.
V. Minerals as Clues to the Source of Sediments.
VI. Correlation by Means of Minerals.
VII. Shore Sands and Dune Sands.
VIII. Deep-Sea Sediments.
IX. Authigenic Minerals.
X. The Mineral Composition of Clays.
XI. Detrital Minerals and the Origin of Metamorphic Rocks.

The dominant theme of the essays is the history of the scientific investigation of these subjects, and the frequent references to the literature cited in the second half make the two parts of the book essentially complementary.

The reader feels at times a sense of disappointment that the essays are not more complete in themselves, as they contain innumerable hints at information falling outside the scope of ordinary text-books, and yet for a fuller development of the particular subject one is referred to the original works. Such, however, is the scheme of the book; it is a guide to further research rather than a self-contained entity, and it must only be hoped that at a later date Professor Boswell will find time to expand more fully the subject of which he here proves himself such a master.

The reviewer finds it a matter of regret that a book, which ought to find an immediate place in every geologist's library, should be narrowed in its sphere of usefulness by being published at the exorbitant price of a guinea. There are neither maps, plates nor text figures to justify such a cost.

G. M. Lees.

Gisements Petroliferes de l'Irak. By C. P. Nicolesco. Paris: Les Presses Modernes, 1933. Pp. x.+221. Fr.50.

Dr. Nicolesco is proving himself to be an indefatigable compiler of geological facts and theories bearing on the oil problems of different countries. It is only a few years since he published a compilation on the oil occurrences of Persia, and now a companion volume on Iraq has appeared. Both these books must be accepted as the best, in fact the only, recent compilations on these subjects in existence, and such faults as may be found with them are, in many cases, the result of inaccuracies or deficiencies in older published works; in other cases the compiler has attempted to make good certain deficiencies or uncertainties by imposing his own opinions on insufficient facts—and the result is not always a success.

The opening chapters on the physical geography, the tectonic elements and the relation of the known oil shows to structural conditions are well written. The structure of Iraq has an almost text-book simplicity when reduced to general terms—although perhaps less so in detail. It can be divided into major elements, a south-west zone bordering the Arabian–Syrian "aire continentale," characterised by flat lying or very gently folded Neogene or Palæogene rocks, followed to the north-east by other structural zones in which the degree of folding increases by successive stages. Oil indications of various types are numerous, ranging from the bitumen lakes of the Hit area to the active oil and gas seepages of the folded zones. Sulphur springs, sulphur deposits and asphaltite deposits are other indications of petroliferous conditions. The Kifri "coal" is a spectacular example of an asphaltite vein in the Upper Fars, and Nicolesco's reference to it is also an example of the dangers which lie in the way of compilers of literature. Pascoe described (mistakenly) how he found a small mass of the "coal" which "*might well have* originated from an isolated tree trunk," and this becomes, in the book under review, a definite statement that "le minerai est associé à des restes végétaux."

The chapters on petrography, stratigraphy and palæontology are good in general terms, but in many cases misleading inferences have been drawn from the published sources. For example, the Valanginian, the lowest rocks described, are mentioned as containing porous dolomites and gypsum, presumably because rocks of this type have been described from S. Persia. The Imam Hasan beds are quite wrongly described as marls, limestones and flysch sandstones with Radiolarites and Loftusia. Mæstrichtian beds of this type are widespread in the north-easterly zone of the Persian and Iraq folded belt, but this zone does not include Imam Hasan. The age of the Asmari limestone and the Fars deposits are discussed in detail, but the problem is made to seem unnecessarily difficult by the presentation of opinions long out of date. The essential fact is that throughout Persia and Iraq a strong limestone divides the lagunar Lower Fars series from the foraminiferal marls of the Eocene and Cretaceous. The age of this limestone phase is not the same throughout and much confusion has arisen by applying the name "Asmari limestone" too liberally. In S. Persia the corresponding limestone is of Oligocene age and was named by Pilgrim the Khamir limestone. At Asmari Mountain the limestone is of Aquitanian and Burdigalian age, but in Iraq the corresponding limestone is mostly of

Oligocene and Upper Eocene age, the true Asmari equivalent being very poorly represented.

The discussion on the Asmari age passes almost imperceptibly over into one on the Cambrian Hormuz of Persia, and a suggestion by de Böckh that some evidence of pre-Cretaceous rocks "might be found in the neighbourhood of Sulaimani," becomes, for Nicolesco, "on trouve trace du faciés hormouz . . . près de Souleimaniyé, au SO de l'Azmir Dagh." This germ of an idea, unfortunately wrongly founded in the first place, must have multiplied exceedingly in the interval between the writing of the text and the preparation of the geological map, in which a long belt of pre-Cambrian rocks are shown passing through Agra and Sulaimani and extending from the Turkish to the Persian frontier. The map otherwise gives a good general picture of the surface geology, although in detail there are many inaccuracies. For example, Qara Chang Dagh is mentioned in the text as containing Palæogene rocks, but this is not shown on the map.

The chapter on tectonics is a useful summary of published literature in so far as this is followed, but the author is on less certain ground when he attempts to interpret the Lower Fars tectonics. His Rumanian experience has given him a strong bias towards diapirism, and his sections are in consequence quite out of keeping with the facts. The author's emphatic advocacy of diapirism, and the sections showing diagrammatically its development in different structures, imply that the views expressed are founded on better evidence than is actually the case. The structural complications of the Iraq folds are due to the incompetence of the salt zone of the Lower Fars, which allows the upper group of rocks to move forward relative to the lower with the formation of thrust faults on the south-west flanks. In no case is there any independent extrusion of the salt group in the way suggested by the diapir hypothesis. The Lower Fars tectonics of the Persian oilfield area are much more complex than anything known in Iraq, due to more intense folding and to a greater development of salt.

In discussing the source rocks of the Iraq oil and the detail of the reservoir rocks the author is greatly handicapped by lack of published material. The presence of lagunar deposits at various horizons in the Tertiary succession has suggested to many workers a connection between them and oil formation, but there is an alternative possibility that the oil has formed in the underlying Eocene and Cretaceous globigerinal marls and migrated up into its present reservoir rock.

The remainder of the book deals with the history of the Iraq oil concessions, from pre-war negotiations to the present day, with the results of the exploration drilling carried out and finally with the pipe-line project for transporting the Kirkuk oil to the Mediterranean. G. M. Lees.